# Comparison of Electromigration in Tin-Bismuth Planar and Bottom Terminated Component Solder Joints

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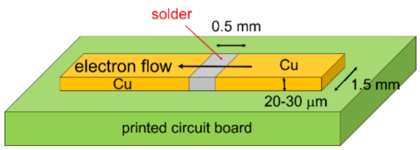
## ABSTRACT
Electromigration monitoring of bottom terminated component (BTC) solder joints is limited to electrical resistance measurements of the solder balls. Tracking the microstructural evolution such as bismuth segregation in tin-bismuth solder ball, is typically via metallurgical cross sectioning, a destructive technique. Once cross sectioned, the solder ball is not available for further electromigration current stressing. A novel planar solder geometry has been invented and developed that allows real-time, non-destructive monitoring of solder microstructure, while the progress of electromigration can be concurrently tracked via electrical resistance means. Planar solder joints are easy to fabricate in a typical metallurgical laboratory. If the electromigration behavior of the planar and the BTC solder joints happen to be similar, the planar solder joint approach could greatly aid in the quick development of solder alloys by comparing the rates of electromigration and the metallurgical changes in planar solders of various compositions. In this paper, the electromigration rates and behavior of eutectic Sn-Bi alloy in planar and in BTC solder joints were compared and shown to be similar. This important finding opens the use of planar solder joints for the quick and low-cost development of low-temperature solder alloys.

Key words: Electromigration, tin-bismuth solder, planar solder, bottom-terminated components, solder joints.

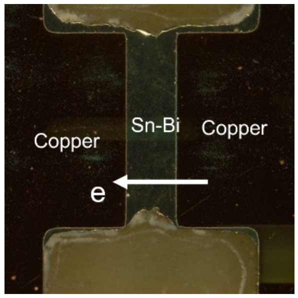
## INTRODUCTION
When the European Union RoHS edict forced the electronics industry to eliminate the use of lead metal in solders, SAC305 solder became the solder of choice for electronic assemblies [1]. Tin-bismuth solder was considered but rejected because the lead-metal containing finishes on components in the supply chain would have reacted with Sn-Bi solder resulting in a very low melting temperature ternary eutectic **[2].** With time as the lead-metal on components in the supply chain got flushed away, the interest in the low melting temperature Sn-Bi eutectic as a solder of choice for electronic assemblies revived for a couple of reasons: One is that at lower soldering temperatures there is less warpage of the assemblies and the second is the energy saving resulting from lower-temperature soldering operations. According to an iNEMI white paper, the deployment of Sn-Bi solder in 1st level packaging is facing two major challenges: high alpha particle emission and electromigration [3].

This paper describes a novel approach to studying electromigration in low-temperature solders such as Sn-Bi eutectic that involves fabrication of a planar solder joint bridging copper traces on a printed-circuit board so that the metallurgical and electromigration phenomena can be directly and non-destructively observed simultaneously with the monitoring of the resistance increase of the solder joint. Planar solder joints of various low-temperature metallurgies can be easily fabricated in a typical metallurgical laboratory and their electromigration behavior quickly and quantitatively studied and compared in a matter of weeks. The validity of the planar solder joint approach in predicting solder electromigration behavior in actual applications such as the bottom terminated component (BTC) solder joints was proven in this paper by showing that the electromigration rates and behavior in planar and in BTC solder joints are very similar.

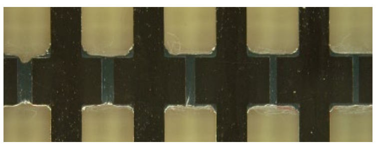
## EXPERIMENTAL METHODS AND RESULTS
### Planar solder joint fabrication and electromigration testing
The planar solder joint method for studying electromigration in low-temperature solders has been described in detail in an earlier paper and is described here briefly **[4]**. Printed circuit boards were fabricated with copper traces with gaps 0.16 to 0.48-mm long and 1.5-mm wide. The gaps were bridged with the solder under test, nominally 30-µm thick, as follows: The gaps were filled with solder paste and covered with 0.1-mm-thick copper foils, followed by reflowing the solder by placing the test assembly in an oven at 180 ºC for 12 minutes. The assembly was cooled, the copper foils peeled off and the exposed solder mechanically ground and polished to obtain the finished test specimen shown in Fig. 1. The resulting test structure consisted of 5 planar solder joints, in series, of




(a) Schematic of a planar solder joint




(b) Sn-Bi planar solder bridging the gap in a copper trace.

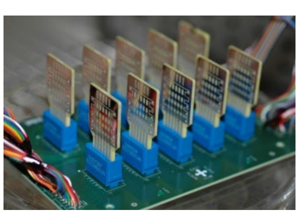
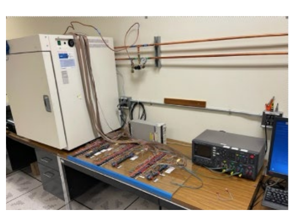


(c) Five Sn-Bi planar solder joints in series. Solder joints had varying lengths to study the effect of solder length on electromigration.

**Figure 1:** Sn-Bi planar solder joint.

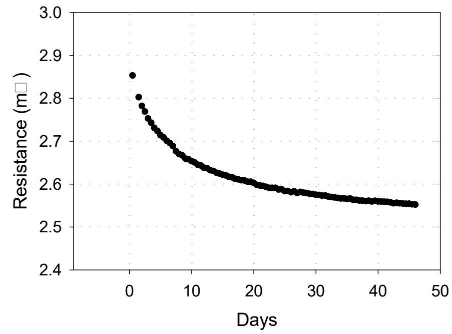
varying lengths, to study the effect of solder length on the rate of electromigration. Ten daughter cards, each with 5 planar solder joints, can be plugged into a motherboard as shown in Fig. 2a. The motherboard was wired to allow passage of current through the planar solder joints and the measurement of voltage across the joints using a data logger. With this 4-point resistance measurement approach, resistance can be measured in the micro-Ohm range. An overall view of the test setup is shown in Fig. 2b. Electromigration test runs were conducted at current densities up to 6.6 kA/cm$^2$ in three oven temperatures (60, 80 and 100 ºC)

Accurate measurement of solder joint temperature is critical to the success of an electromigration study. The resistances of the solder joint were measured at a very low current (100-250 mA), low enough to avoid Joule heating, at room temperature and at the temperature of the electromigration test. The coefficient of electrical resistance thus determined was used to calculate the temperature of the solder joints at the start and the end of each electromigration test run.

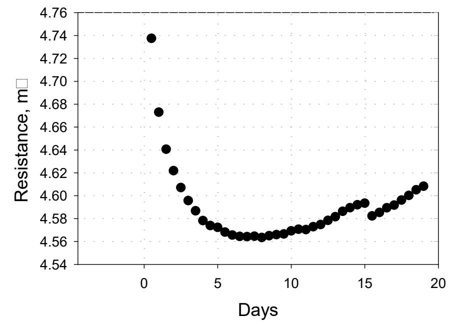



(a) (b)

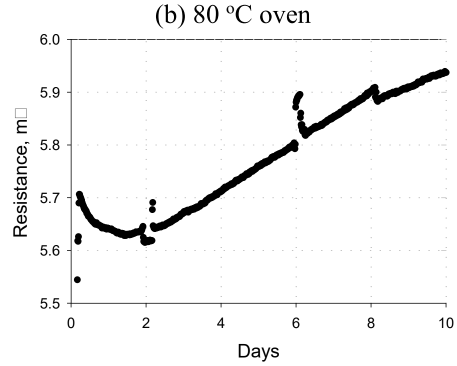
**Figure 2:** (a) 10 daughter cards plugged in to a motherboard; (b) over all view of test setup.




(a) 60 ºC oven




(b) 80 ºC oven



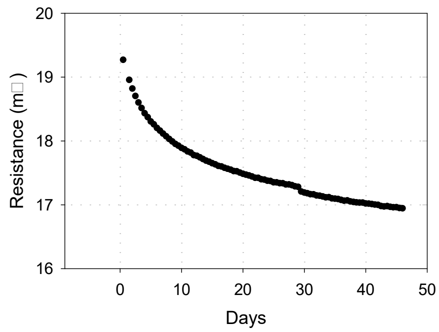

(c) 100 ºC oven

**Figure 3:** Effect of oven temperature on the temporal resistance behavior of planar solder joints at 1 Amp current (2.2 A/cm$^2$).

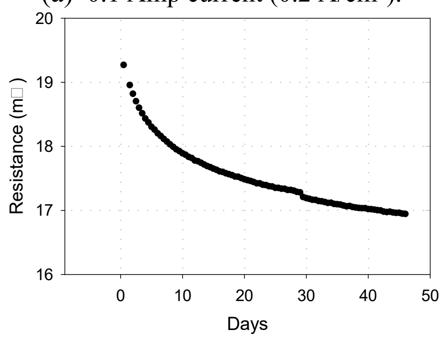
The rates of electromigration in the planar solder joints were measured two ways: (1) rate of change of solder joint electrical resistance as shown in Figures 3 and 4 and (2) rate of increase of the length of the segregated bismuth at the anode as shown in Figures 5 and 6.

**Bottom-terminated component solder joint fabrication and electromigration test**

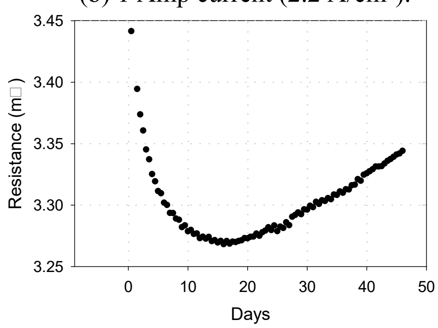
The bottom-terminated component (BTC) solder joints were fabricated to bridge two stacked printed circuit cards. Figure 7 shows a 5x5 mm printed circuit card, representing a component, on the top of a daughter card with an edge card connector that plugs into a motherboard from where wires lead to power supplies and a data logger. The 38 solder joints between the two cards form a square so that the 5x5-mm card floats parallel to the daughter card during the solder reflow step. Only 4 of these solder joints come into play during the electromigration step as explained in Fig. 7. The tops of these 4 solder joints are electrically shorted on the 5x5-mm card



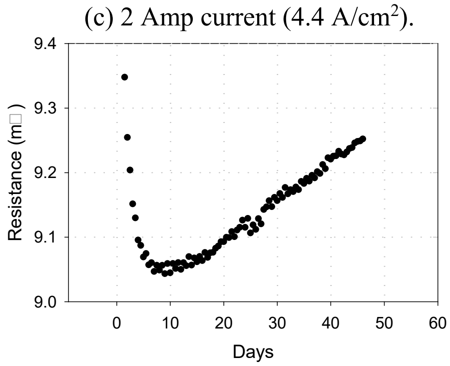

(a) 0.1 Amp current (0.2 A/cm$^2$).




(b) 1 Amp current (2.2 A/cm$^2$).




(c) 2 Amp current (4.4 A/cm$^2$).




(d) 3 Amp current (6.6 A/cm$^2$).

**Figure 4:** Effect of magnitude of current on the temporal resistance behavior of planar solder joints in 60 ºC oven at (a) 0.1 Amp current (0.2 A/cm$^2$); (b) 1 Amp current (2.2 A/cm$^2$); (c) 2 Amp current (4.4 A/cm$^2$ ) and (d) 3 Amp current (6.6 A/cm$^2$ ).

side. The circuitry on the daughter card allows the electromigration current to only flow through the solder joints 2 and 3. The voltage across solder joint 2 is measured on the daughter card side between pads 1 and 2; and the voltage across joint 3 is measured on the daughter card side between pads 3 and 4. No current flows though solder joints

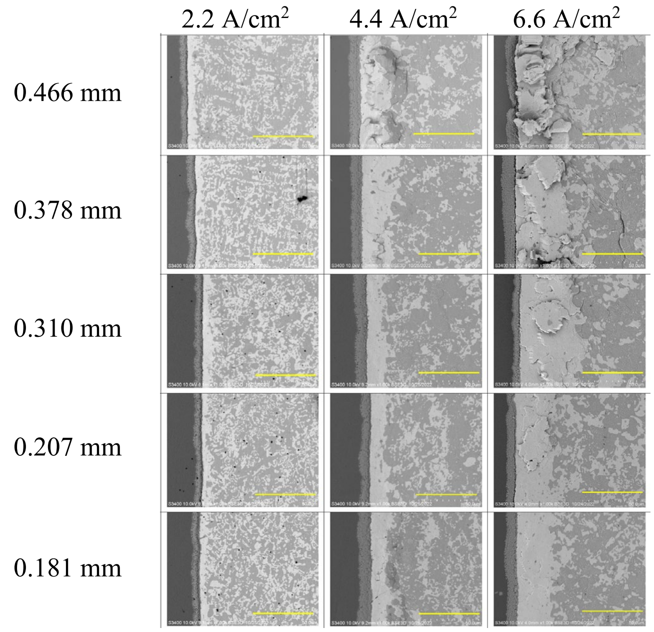



**Figure 5:** Scanning electron micrographs of eutectic Sn-Bi planar solder joint in 100 ºC oven. Electron current flowed from right to left. The lighter phase is Bi rich and the darker phase is Sn rich. The left column lists the joint gaps.

1 and 4. Thus, the resistances of the solder joints 2 and 3 are measured using the 4-point approach.

The rates of electromigration in the BTC joints were tracked electrically as changes in the electrical resistance of the joints as shown in Figures 8 and 9. Two daughter cards, each with 2 solder joints, were employed in the test under 4 oven temperatures starting with 100 ºC, followed by 80 ºC, 120 ºC and lastly at 60 ºC. Figure 10 shows an example of BTC solder joint cross sectioned after some electromigration stressing. The migration of the Bi towards the anode and its depletion on the cathode side is evident.

Let us address the question of how best to summarize the electromigration results so that they are useful in predicting the electromigration life of a solder joint: Let us start with Nernst-Einstein equation [5] relating the bismuth atomic drift velocity to bismuth material properties (diffusion coefficient D, effective valence Z* and resistivity ρ) and to the electric current density j and temperature T.

$$v = \frac{DF}{kT} = \frac{DZ^{*}e\mathrm{E}}{kT} = \frac{DZ^{*}e\rho j}{kT}$$

Rearranging terms, we get

$$\frac{vT}{j} = \frac{DZ^{*}e\rho}{k} = \frac{D_0 Z^{*}e\rho}{k} e^{-\frac{Q}{kT}}$$

where Q is the diffusion activation energy. With the reasonable assumption that the bismuth atomic drift velocity v is proportional to the rate of change of resistance of the solder joint, we can say that $v = (\text{contant})\Delta R / days$, leading us to the final equation we can use to summarize the entire electromigration data in the form of an Arrhenius plot,

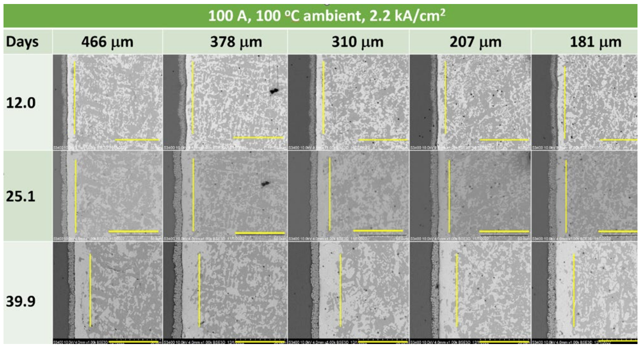



**Figure 6:** Scanning electron micrographs of eutectic Sn-Bi planar solder joint in 100 ºC oven showing the extent of segregation as a function of electromigration time from 12 to 40 days and the solder joint length varying from 0.181 to 0.466 mm. Electron current flowed from right to left. The lighter phase is Bi rich and the darker phase is Sn rich. The left column lists the joint gaps.

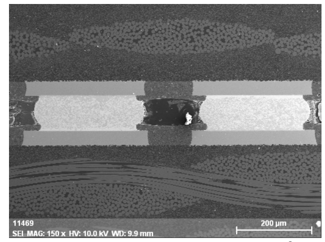
$$\frac{(\Delta R/days)T}{j} = Ae^{-\frac{Q}{kT}}$$

where A is just a constant of proportionality.

The results of the planar and the BTC solder joints are summarized in Fig. 11. The Arrhenius plot shows the effect of current density and solder temperature on the rate of electromigration.

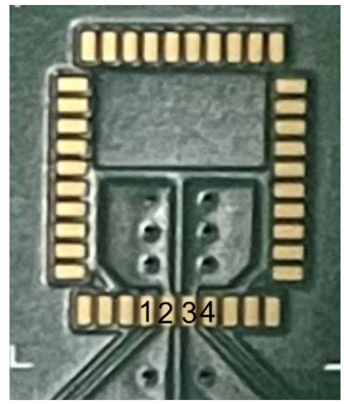
**DISCUSSION**

Before we discuss the electromigration results, let us explore the Sn-Bi phase diagram and the kinetics of the Sn-rich phase achieving thermodynamic equilibrium, that is, achieving the composition predicted by the solvus line on the Sn-rich side of the binary phase diagram shown in Fig 12. The Sn-rich phase has ~ 21 wt. % Bi dissolved in it at 138 ºC, a little below the eutectic temperature of 138.5 ºC. As the temperature decreases below the eutectic, the equilibrium concentration of Bi in the Sn-rich phase follows the solvus line, decreasing from ~ 21 wt % at 138 ºC to ~ 2 wt. % at room temperature. However, the as-cast, rapidly cooled, non-equilibrium structure of Sn-Bi eutectic would retain most of the ~21 wt % Bi in the Sn-rich phase at room temperature. With time, the thermodynamic driving force would lower the Bi concentration in the Sn- rich phase, via the Bi atoms diffusing to the Bi-rich particles dispersed in the Sn-rich phase matrix and to some extent by Bi particles precipitating in the Sn-rich phase. The rate of this drive to equilibrium would be slower at lower temperatures. The time required for the Sn-rich phase to achieve equilibrium composition as per the solvus line would be approximately equal to $\tau = l^2 / \pi^2 D$, where l is the half the mean size of the Sn-rich phase regions between the Bi-rich particles and D is the diffusion coefficient of Bi in polycrystalline Sn **[6].** In the section on homogenization, Reed-Hill describes the relaxation time τ as the time required to make a function that depends exponentially on time to decrease in value by a factor of 1/e.

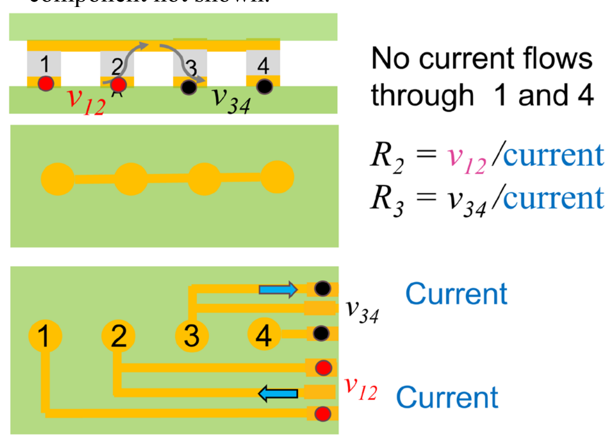



(a) Solder joints (0.60x0.25 mm$^2$) between a component on top and PCB on the bottom.


(b) Top view of a BTC test specimen.



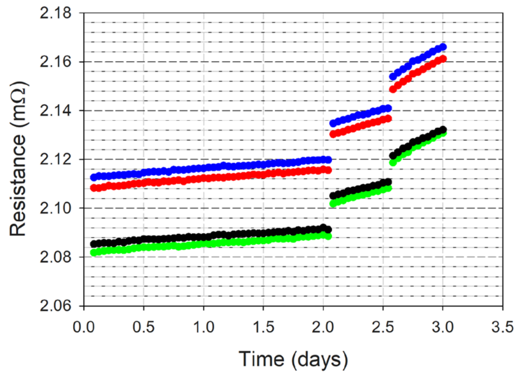

(c) View of test printed circuit board with the top component not shown.



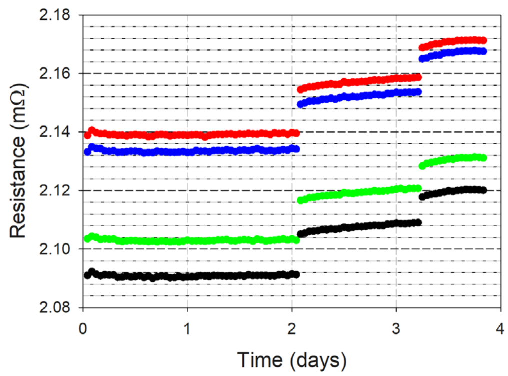

(d) Explanation of the 4-point resistance measurement of solder joints 2 and 3.

**Figure 7:** Bottom terminated test setup for studying solder joint electromigration.

Electromigration in Sn-Bi solder involves bismuth atoms drifting faster than the tin atoms, resulting in bismuth segregation on the anode side of the solder and loss of bismuth on the cathode side. Given enough time, a Bi-rich phase develops a continuous layer on the anode side while the cathode side gets depleted of the Bi-rich phase. Meanwhile, as the Bi atoms are migrating towards the anode side, the as-cast eutectic non-equilibrium structure evolves by the excess bismuth in the Sn-rich phase diffusing to the Bi-rich particles and to some extent precipitating out in the Sn-rich phase. The resulting purer state of the Sn-rich phase makes it electrically more conductive. Therefore, from the

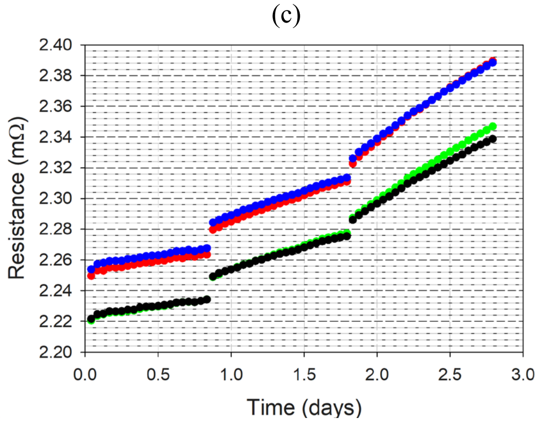



(a) 100 ºC oven.




(b) 80 ºC oven.

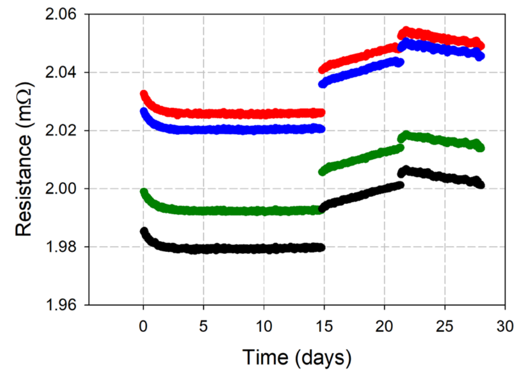
(c)



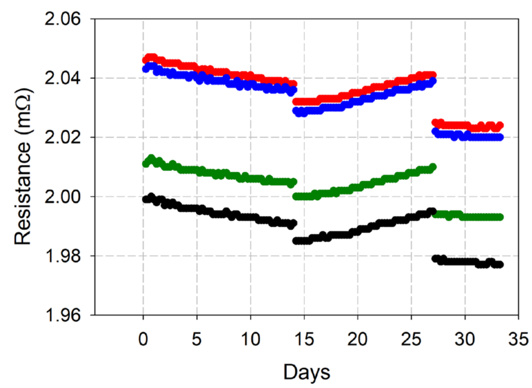

(c) 120 ºC oven

**Figure 8:** Bottom terminated component (BTC) solder joint resistance versus time as a function of oven temperature and current. Data for 2 daughter cards, with two solder joints on each card, are shown. The curves are over three-time periods; the first at 2 A, the second at 4.2 A and the third at 6.2 A current. The sequence of testing started with testing in 100 ºC oven followed by 80 ºC, 120 ºC and 60 ºC. The 60 ºC test run results are shown in Fig. 9.

point of view of the solder joint resistance change, two phenomena are occurring: The Sn-rich phase is becoming purer and therefore more conductive, contributing towards the decreasing of the resistance of the solder joint; and the electro migrating Bi atoms are segregating towards the anode forming a uniform Bi layer and thus contributing towards increasing the resistance of the solder joint. The duration of




(a) First test run in 60 ºC oven




(b) Second test run in 60 ºC oven

**Figure 9:** This figure is a continuation of Fig. 8. Above test runs in 60 ºC oven were after those shown in Fig. 8. The curves are over three-time periods; the first at 4.2 A, the second at 6.2 A and the third at 2 A current

this initial stage is the time it takes for the Sn-rich phase to homogenize and achieve the composition predicted by the solvus line which is approximately equal to $\tau = l^2 / \pi^2 D$. This initial stage can be cut short by the Bi atoms segregating on the anode side to form a continuous layer. Once a continuous Bi layer forms, the solder joint can be described as a low resistance Sn-rich phase matrix in series with a high resistance Bi layer. The joint resistance is now dominated by the Bi layer and increases with time as the Bi layer thickens.

The effect of temperature on the duration of the period of decreasing resistance in the early stages of electromigration

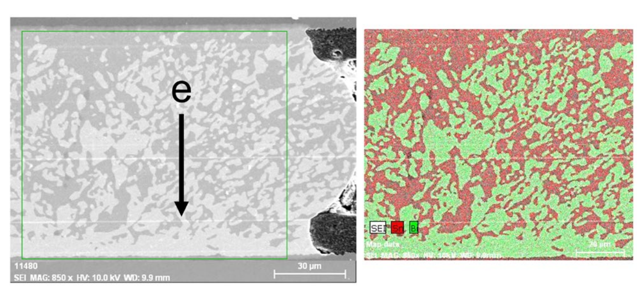



**Figure 10:** Scanning electron micrograph of a BTC solder joint cross section and an elemental map of the cross section. The green region is Bi-rich phase and the orange region is Sn-rich matrix.

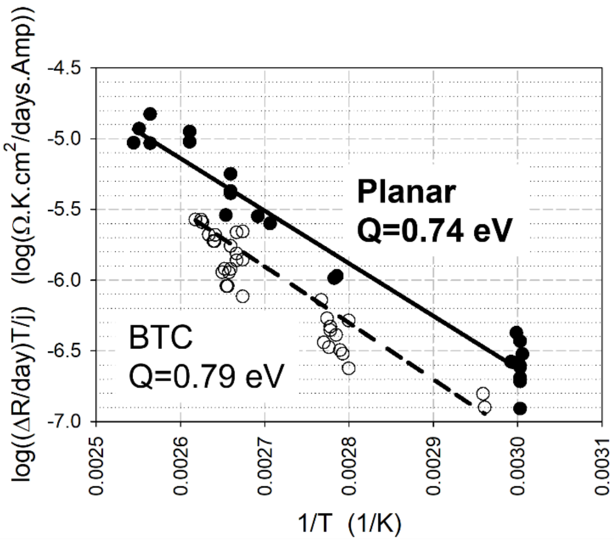



**Figure 11:** Arrhenius plot of Bi electromigration in eutectic Sn-Bi solder using the planar and the BTC approach.

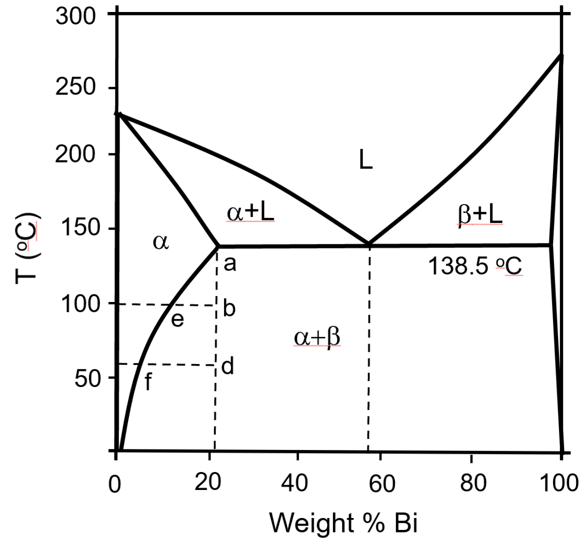



**Figure 12:** Sn-Bi phase diagram

in planar solders is shown at three different oven temperatures at 1 A electric current in **Fig. 3**. As the oven temperature increases, the initial period of decreasing resistance shortens. This effect can be explained based on the dependance of the relaxation time τ on temperature as listed in **Table 1**. The magnitude of τ at various temperatures in **Table 1** is similar to that of **Fig. 3**. So in summary, the reason for the decreasing solder joint resistance during the early stage of electromigration is the reduction of the Bi content of the Sn-rich phase matrix through with most of the electric current flows.

The effect of electric current on the temporal behavior of planar solders in 60 ºC oven is shown in **Fig 4**. At higher currents, the initial period of decreasing resistance is shorter. The effect of the magnitude of current can be explained based on research on electro-dissolution of the Bi-rich phase in Sn5Bi alloy **[7].** In this work, it was shown that high currents can result in the dissolution of the Bi from the Bi-rich phase into the Sn-rich phase matrix thus increasing the electrical resistance of the Sn-rich phase matrix through which most of the current flows.

The BTC electromigration tests were conducted on only 4 solder joints. These solder joints were subjected to 2, 4.2 and 6.2 A currents in sequence with oven temperature first at 100 ºC, then at 80 ºC followed by 120 and 60 ºC. The effects of oven temperature and current on the resistance behavior BTC solder joints are shown in Fig. 8 and 9. The electromigration test runs at 80 ºC and above show no period of decreasing resistance. Following these relatively high oven temperature runs, the 4 solder joints were tested at 60 ºC oven temperature. Following the test run at 120 ºC, the run at 60 ºC and 2 A current showed a long period of decreasing solder joint resistance similar to that observed in planar solder joints. The explanation for this period of decreasing resistance is the same as that for the planar solder joints. However, a new phenomenon was observed in these 4 BTC joints at 6.2 A current in 60 ºC oven: It was repeatedly observed that the resistance decreased with time under only this specific condition of 6.2 A current in 60 ºC oven. More work is need to explain this anomalous but very interesting behavior.

**Table 1:** Time for the Sn-rich phase to achieve equilibrium composition as per the solvus line. The diffusion D values are from reference 7.

| **Temperature, ºC** | **D (cm²/s)** | $\tau = l^2 / \pi^2 D$ **(days)** |
|---|---|---|
| 60 | $10^{-12.6}$ | 42 |
| 80 | $10^{-11.6}$ | 4 |
| 100 | $10^{-10.2}$ | 1.6 |

The results of this work summed up in the Arrhenius plots of Fig. **11** prove that the electromigration behavior of planar and BTC solder joints are similar within the limits of the experimental error. The validation of planar solder joints as a reliable vehicle to rank solder alloys from an electromigration point of view is a boon to the rapid development of solder alloy metallurgies with low propensity for electromigration.

## CONCLUSION

The study concluded that the planar and the bottom terminated component (BTC) solder joints have very similar electromigration behavior. They both show an initial period of decreasing electrical resistance in the early stages of the test under low temperature and low electric current density conditions. At high temperatures and high current densities this initial period of decreasing electrical resistance shortens. The Arrhenius plots that conveniently sum up the effect of temperature and current density on electromigration are also very similar for the planar and the BTC solder joints.

Planar solder joints are easy to fabricate. They allow the monitoring of electromigration and microstructure changes simultaneously with electrical resistance changes. BTC solder joints are much more complicated to fabricate. In addition, the electromigration behavior of bottom terminated component solder joints can only be tracked by their electrical resistance. The conclusion that the electromigration behavior of planar and BTC solder joints is similar is very beneficial: It allows the use of the easier to fabricate planar solder joints to study the electromigration behavior of various solder metallurgies. The development of solder metallurgies can thus be greatly shorted and can be conducted at much lower cost.

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