Sn-Bi and SAC305 solder metallurgy and electromigration

Prabjit (PJ) Singh

singh.prabjit@gmail.com

RPI degrees: Prabjit Singh, MS in EE; Vassar Prof Sarjit Kaur, PhD in Polymer Chemistry

iNEMI team
(International Electronics Manufacturing Initiative)

Name	*Company*
Larry Palmer	*IBM*
[redacted]	
Tom Wassick	
[redacted]	
Raiyo Aspandiar	*Intel Corporation*
Brian Franco	

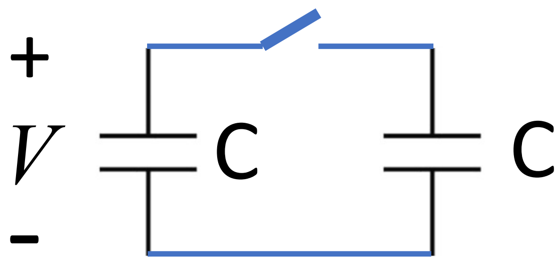
Name	*Company*
Richard Coyle	*Nokia*
[redacted]	
Vasu Vasudevan	*Dell*
Aileen Allen	*HP, Inc*
Keith Howell	*Nihon Superior*
Kei Murayama	*Shinko*

Name	*Company*
Hongwen Zhang	*Indium Corporation*
Anna Lifton	*MacDermid Alpha, Electronic Solutions*
Murali Sarangapani	*Heraeus Materials*
Terry Munson	*Foresite, Inc*
Steven Middleton	
Haley Fu	*iNEMI*

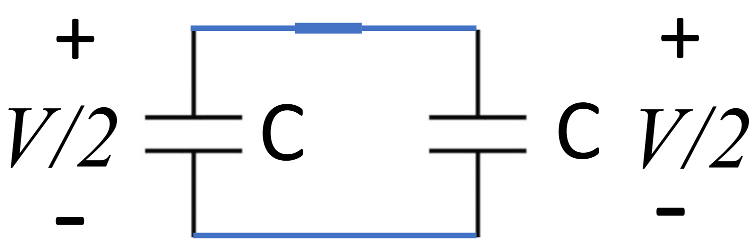
Back to kindergarten

Come to school full of joy, communicate, share your work and knowledge, contribute to a happy workplace and be forever curious.

Your curiosity index (How curious are you?)



$$E = \frac{1}{2} C V^2$$

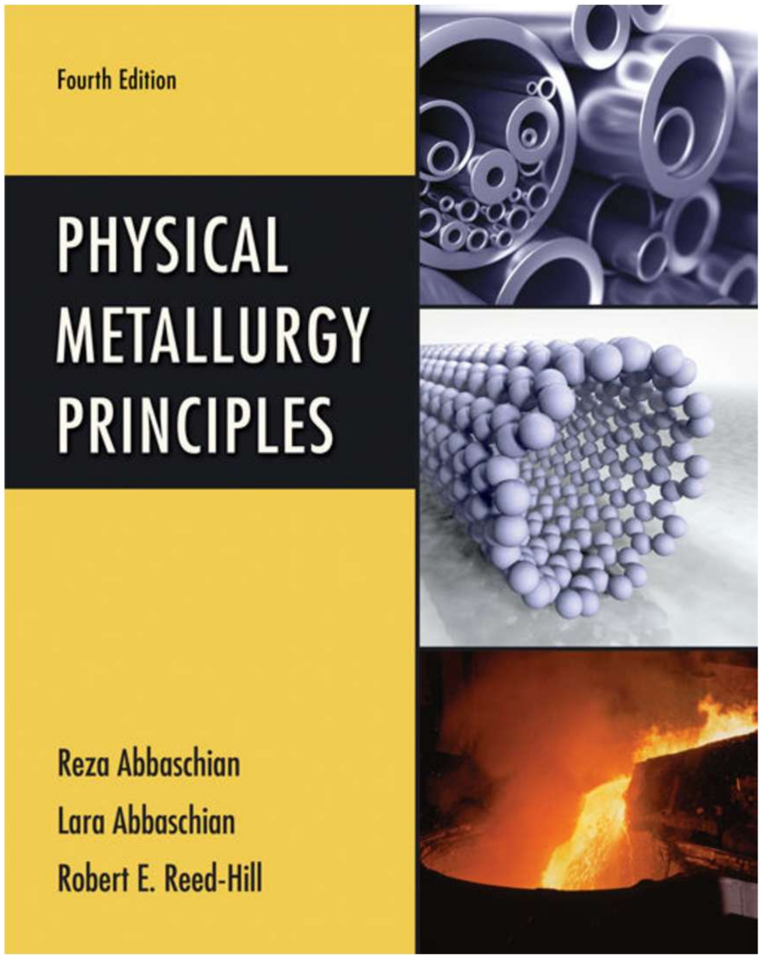


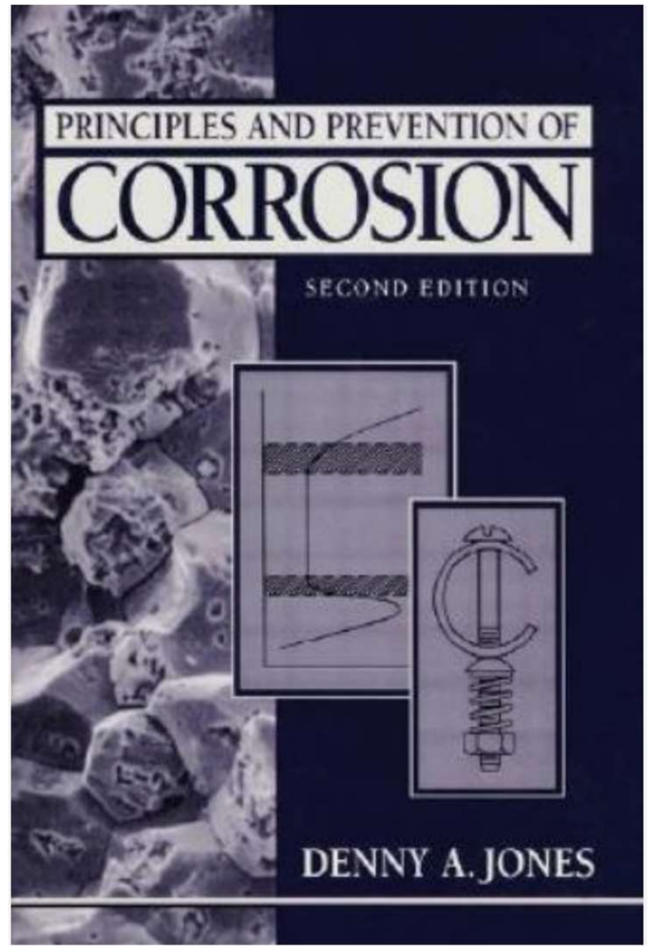
$$E = \frac{1}{2} C \left(\frac{V}{2} \right)^2 + \frac{1}{2} C \left(\frac{V}{2} \right)^2 = \frac{1}{4} C V^2$$

Derive the volume common to two orthogonally intersecting cylinders?

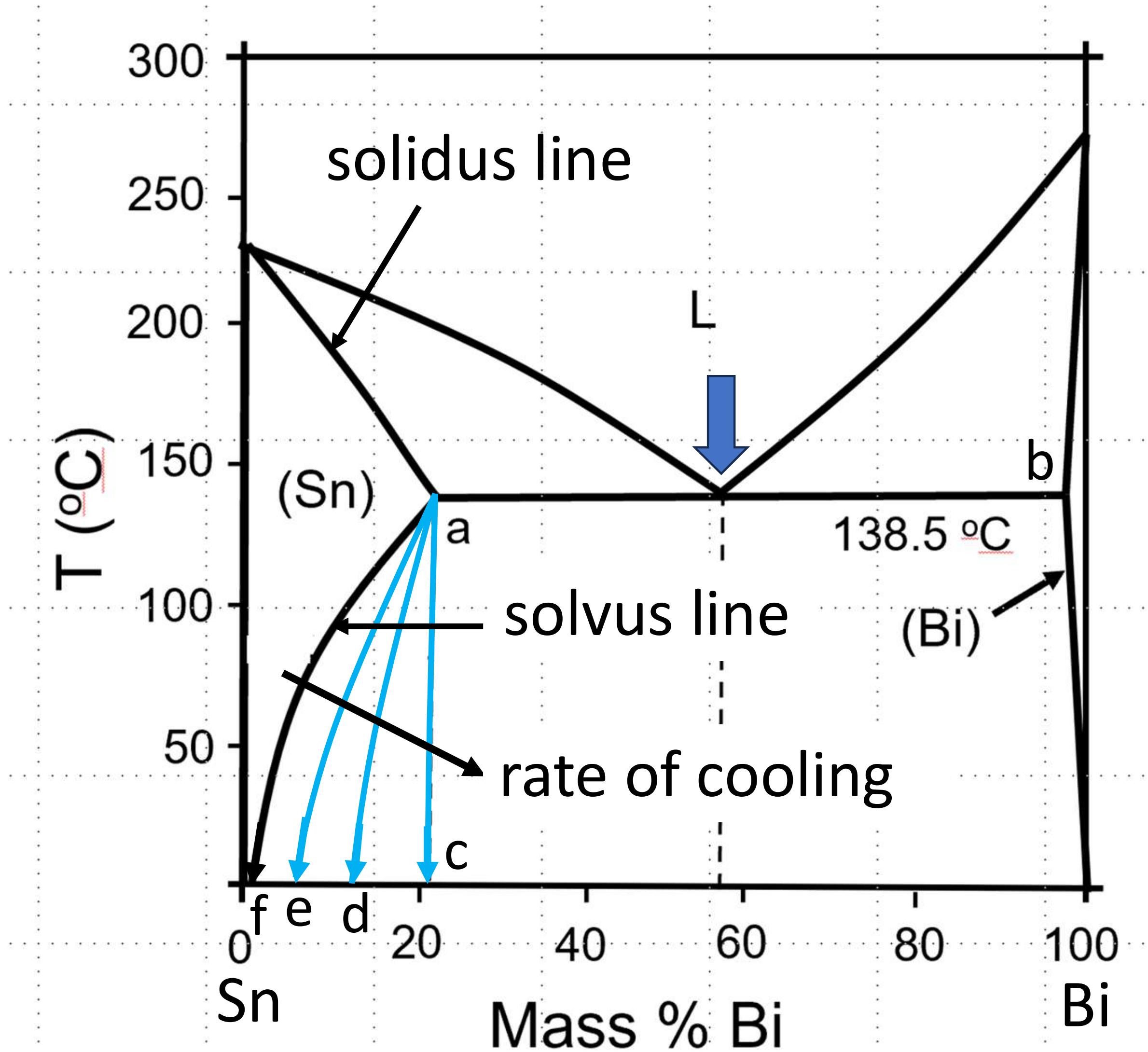
PJ Singh
+1-845-489-4349
singh.prabjit@gmail.com

Two textbooks on my desk for 4 decades

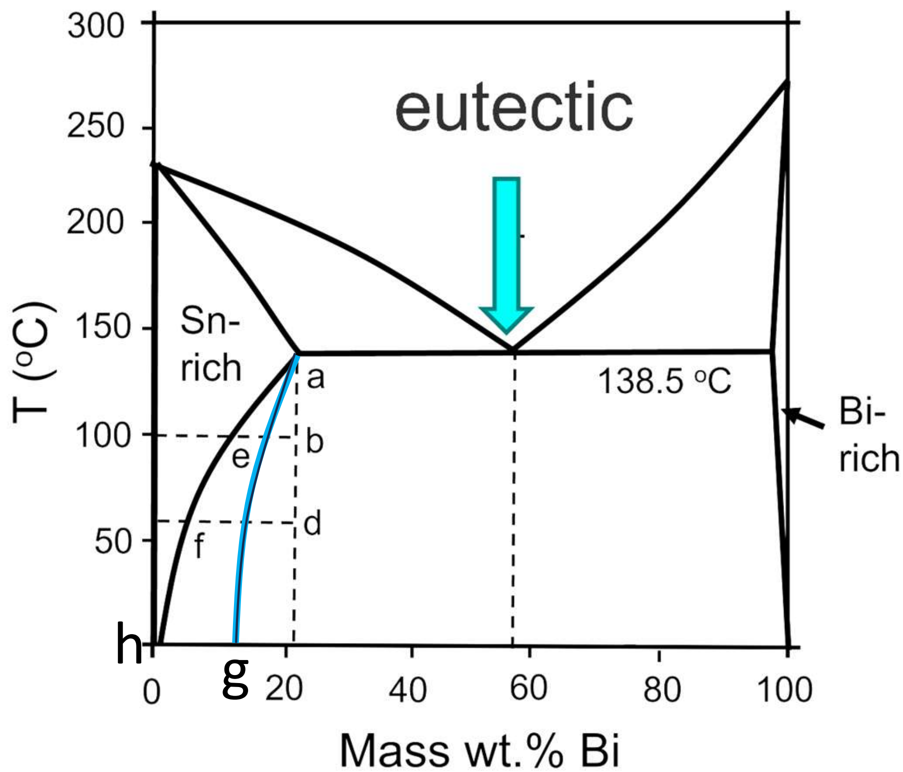


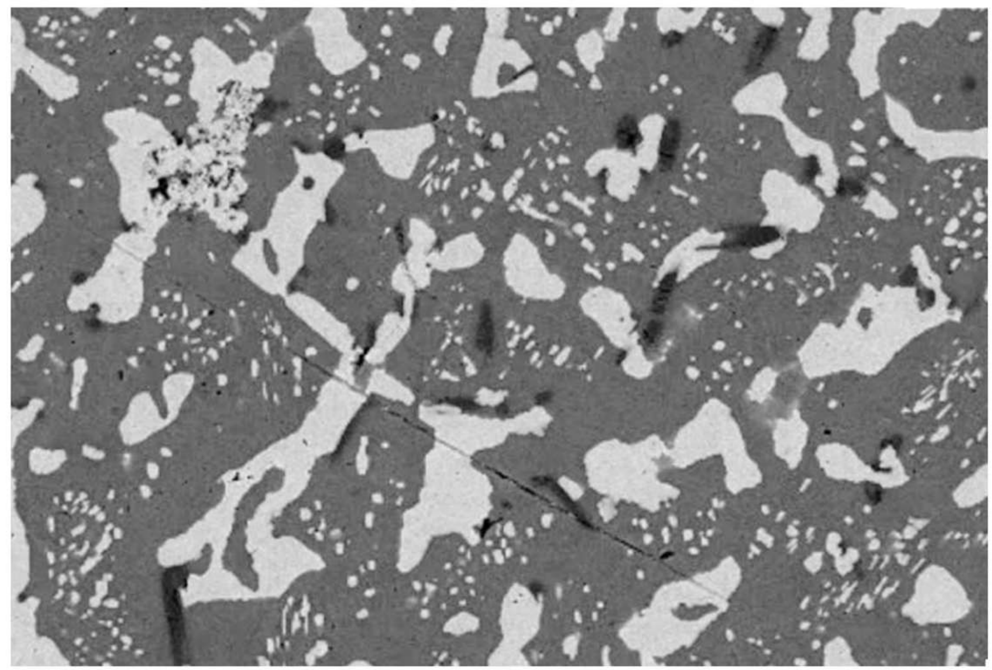


Just below the eutectic temp, Sn-Bi forms a Sn-rich phase of Bi content = 21 wt. % (point a). With super fast cooling, the Sn-rich phase Bi content remains at 21 wt % at room temp. With extremely slow cooling the Sn-rich phase composition follows the solvus line.



Tin-bismuth alloy phase diagram and microstructure





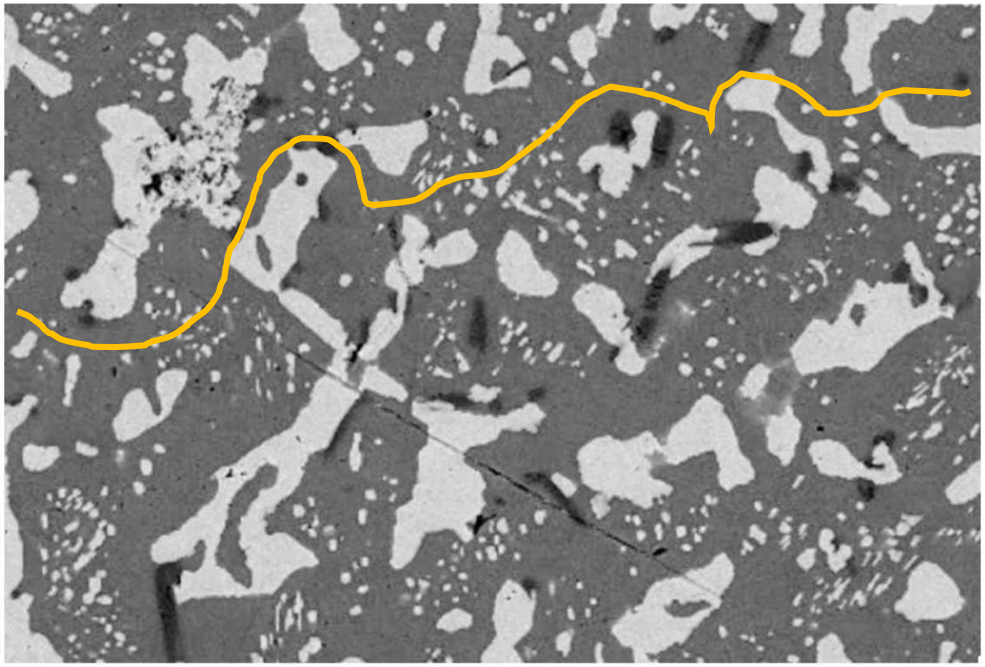
Bi-rich phase in Sn-rich matrix

Bright phase is Bi rich, dark phase is Sn rich. Notice the small Bi-rich particles between the large Bi-rich particles in the Sn-rich matrix. Why?

Path electric current follows in tin-bismuth alloy

Sn resistivity = 11.5 μΩ.cm
Bi resistivity = 129 μΩ.cm

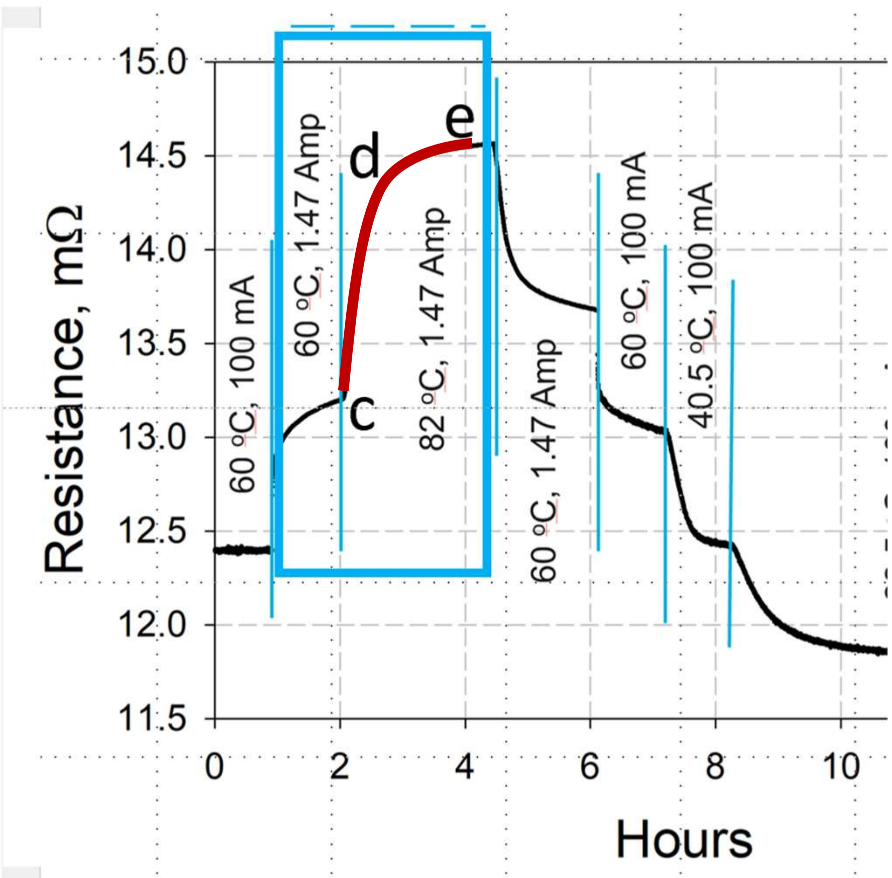
Electric current takes the path of least resistance.
It flows mostly through the Sn-rich phase, avoiding the Bi-rich phase.

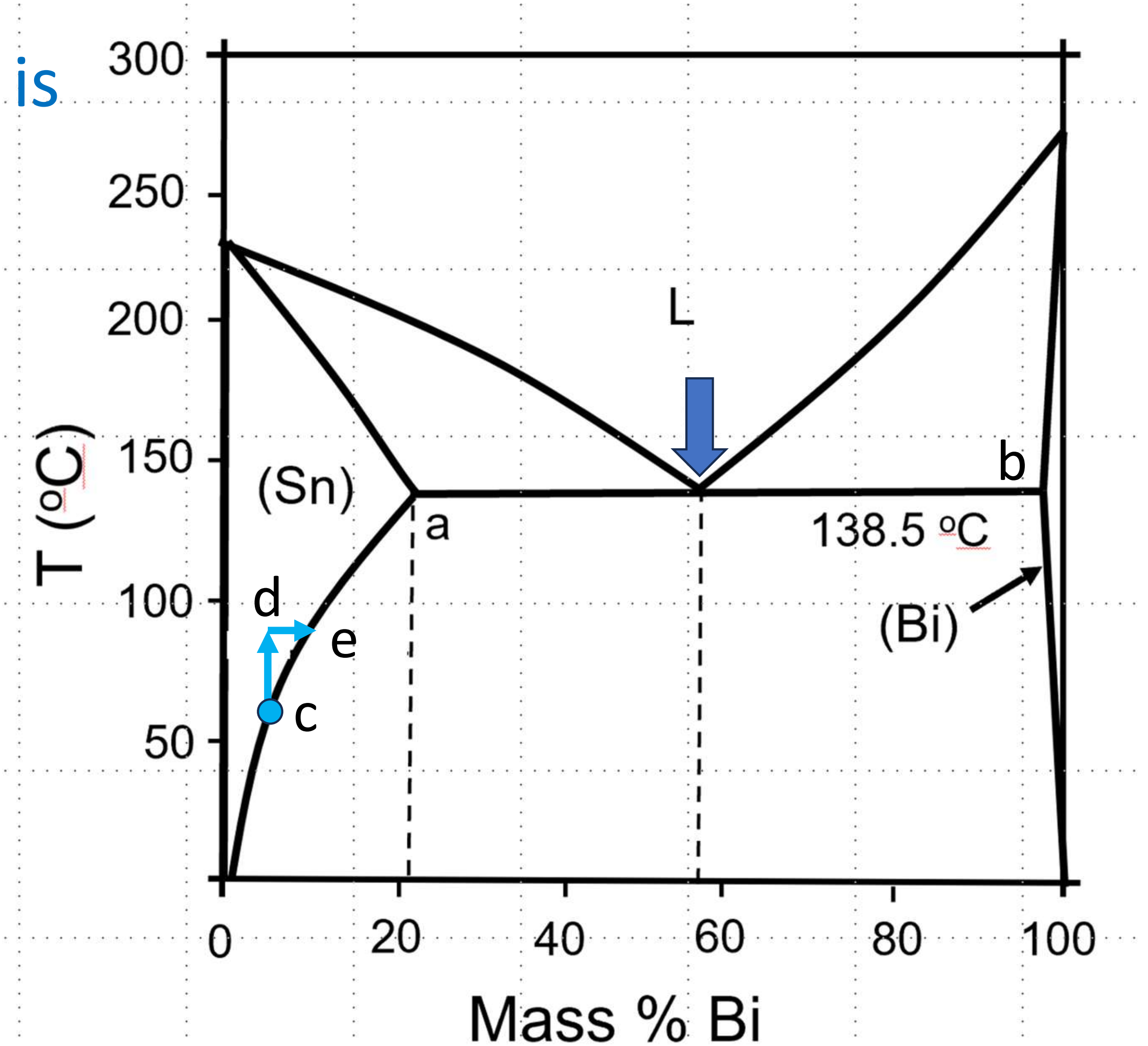


Bi-rich phase in Sn-rich matrix

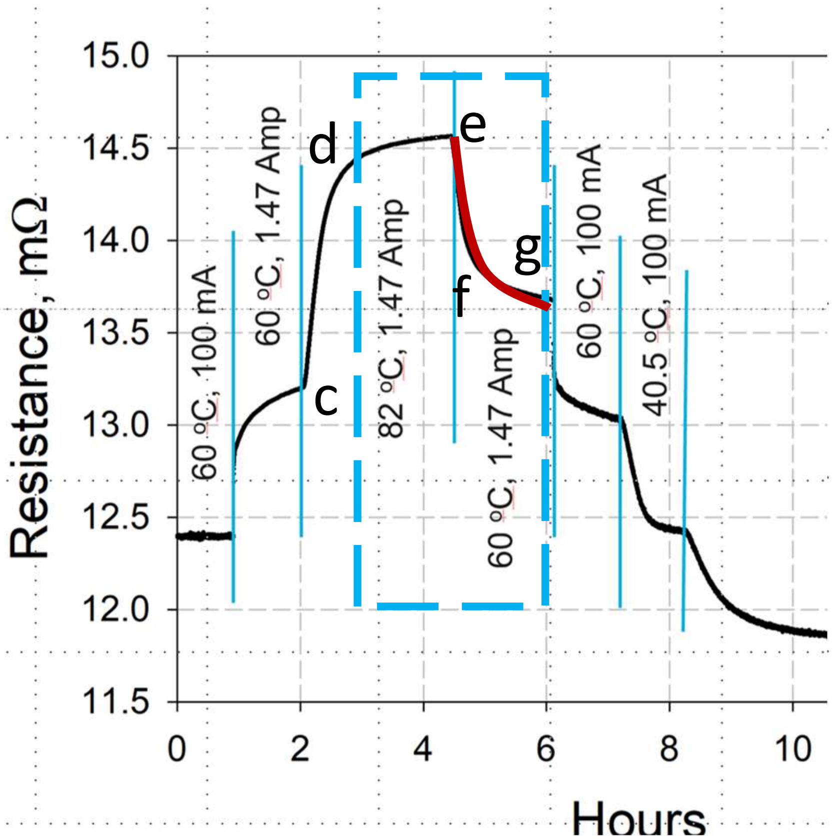
The bright phase is Bi rich, dark phase is Sn rich.

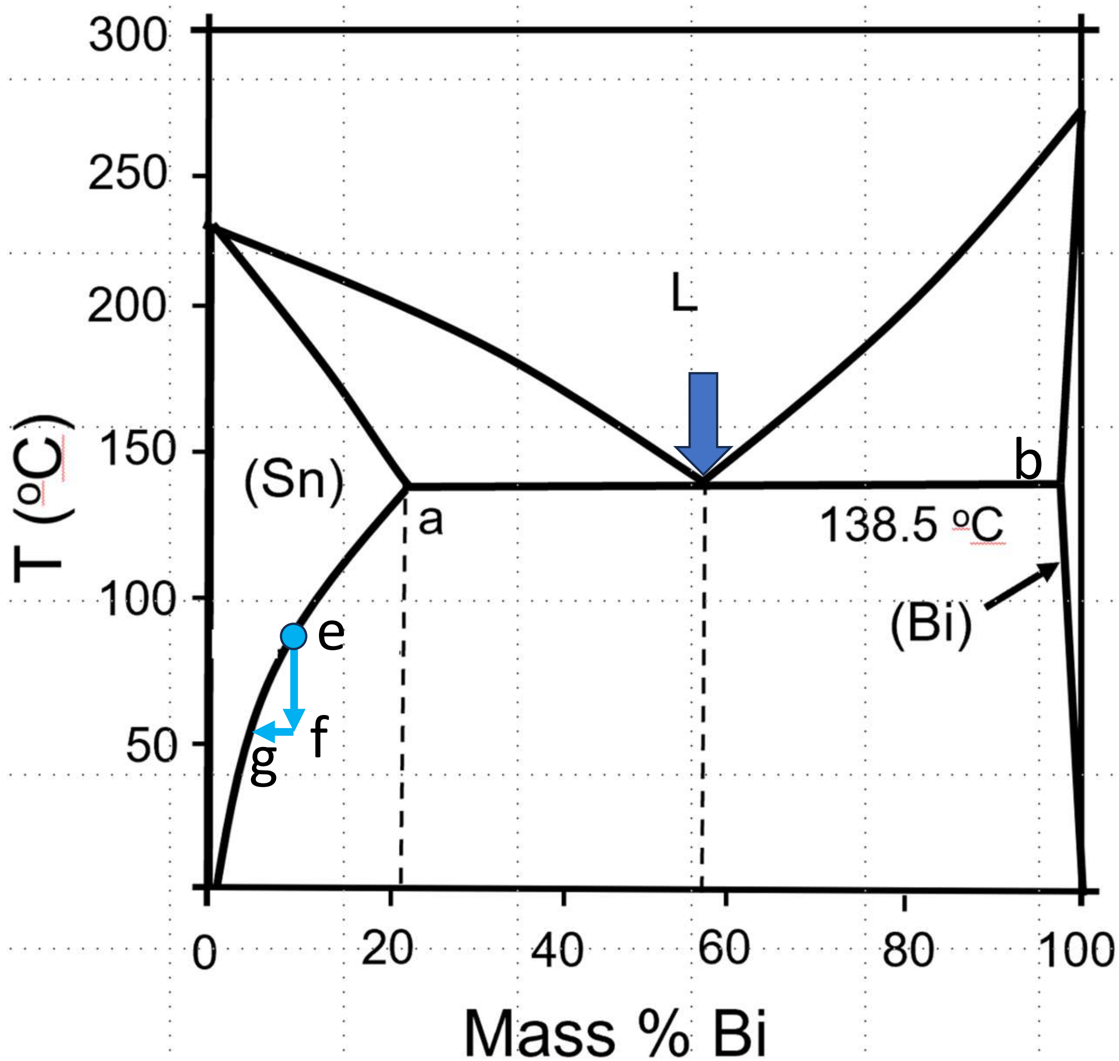
What happens when temp is raised from 60 to 82 °C?





What happens when temp is lowered from 82 to 60 °C?





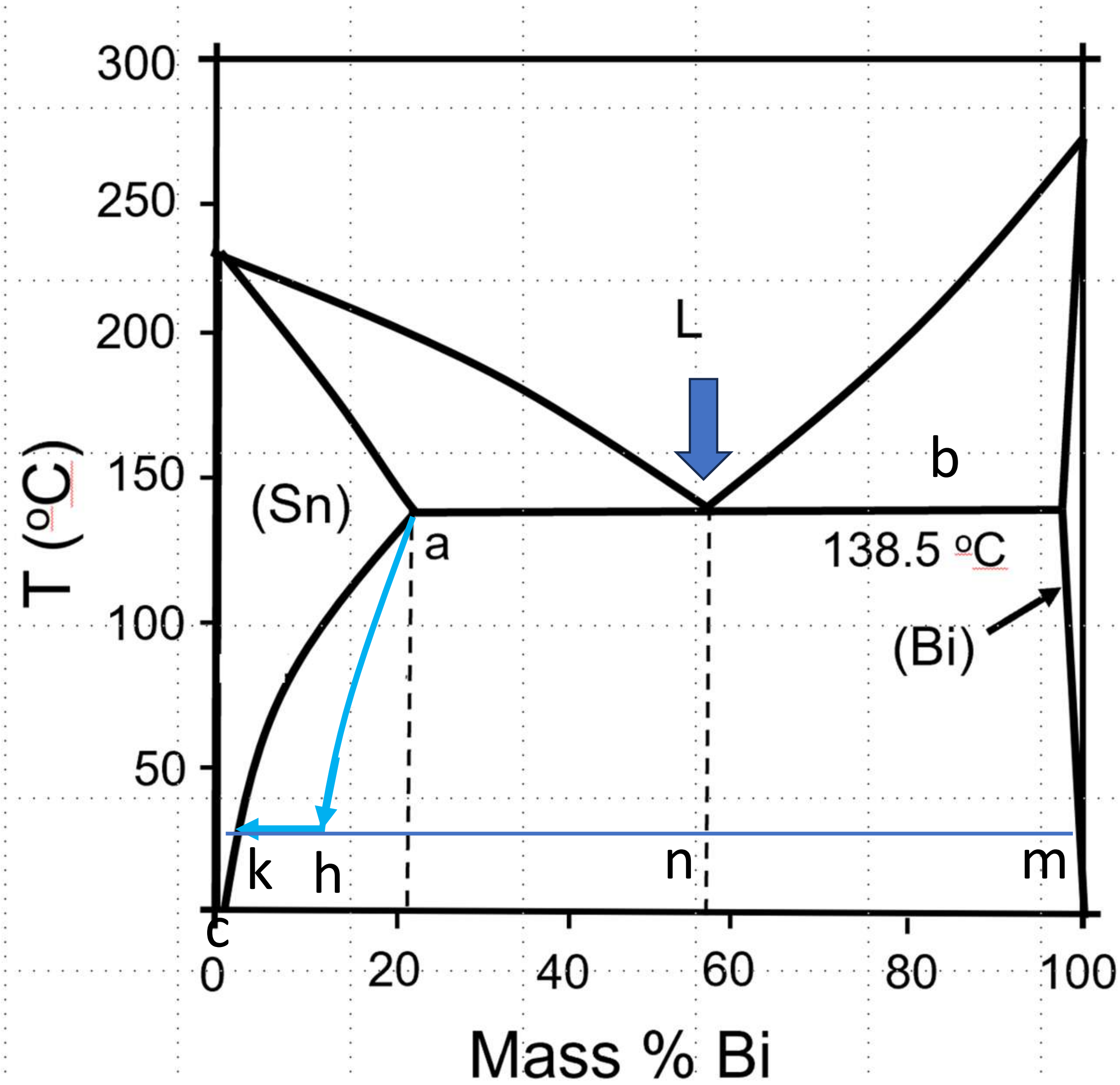
When can happen when a Sn-Bi alloy is aged at room temperature?

The as-cast Sn-rich phase comp at t=0 could be at h.

When aged, the comp which is at h tends to k.

By the lever rule, the wt fraction of the Bi-rich phase **increases** from hn/hm to kn/km.

The mass fraction of the Bi-rich phase can never decrease when aged at room temperature

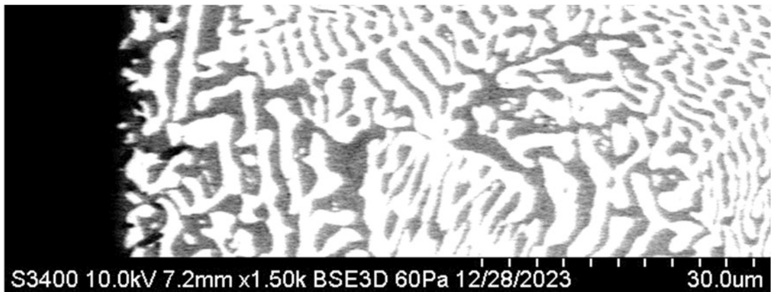


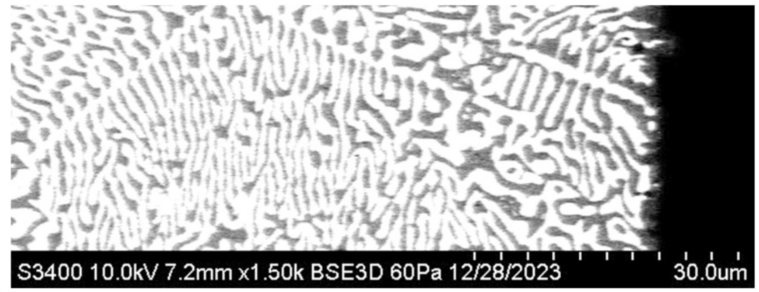
Sn-57Bi-0.4Ag aged at 83 °C

Cathode

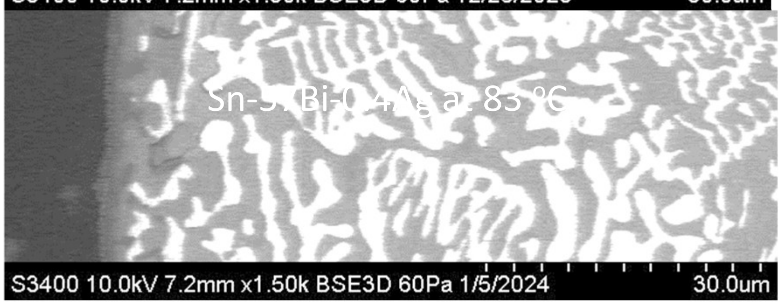
Anode

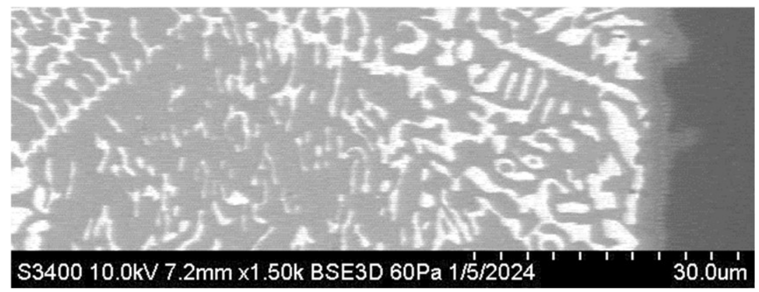
Day 0



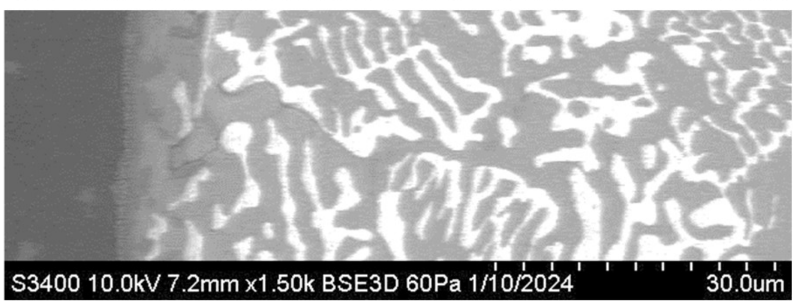


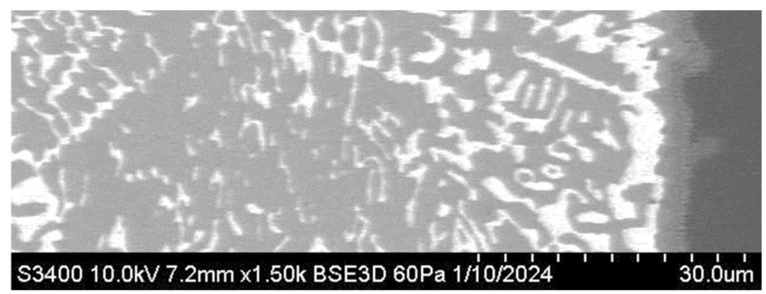
Day 4





Day 8

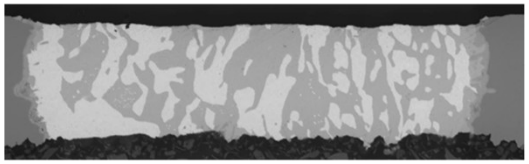


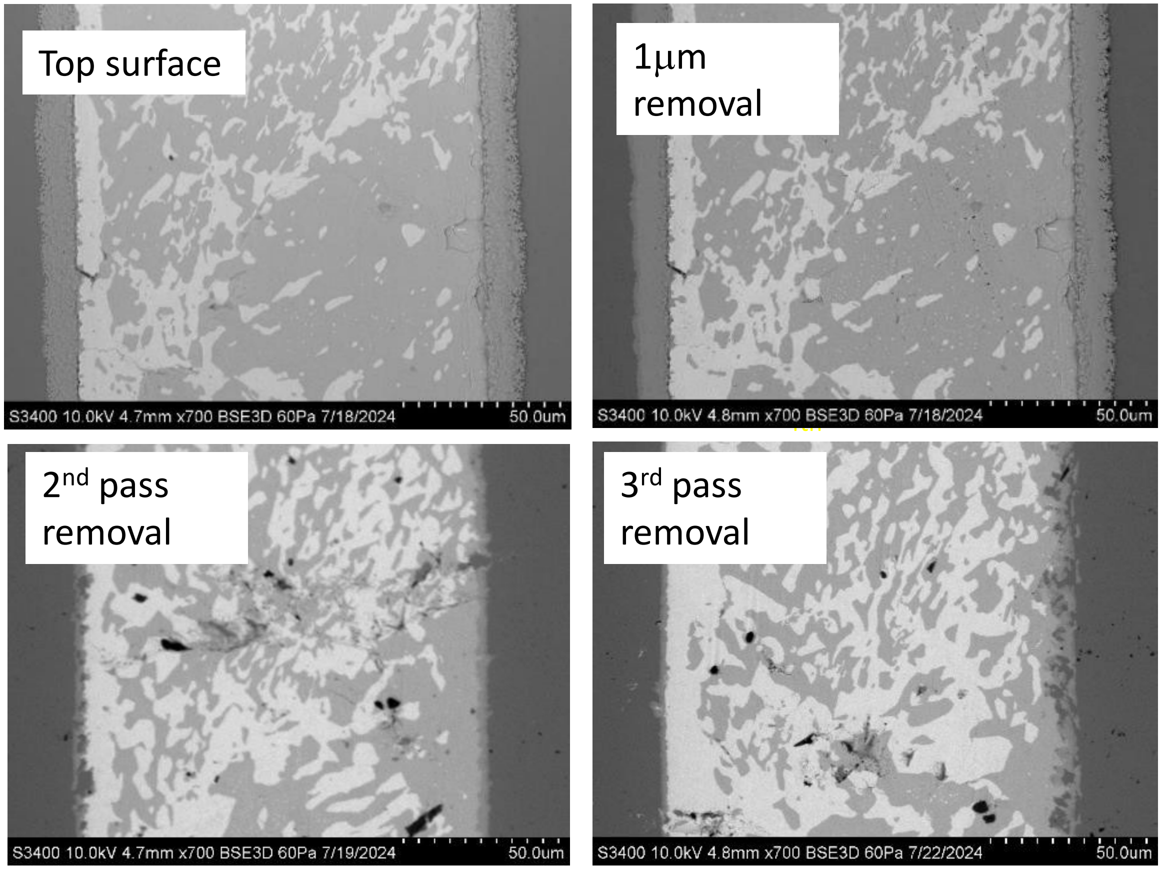


When making conclusions on microstructural changes of Sn-Bi alloy make sure you use freshly cross sectioned specimens

The reason for freshly prepared specimens is that we have observed that the Bi-rich phase sinks into the body of the alloy over time.

This may be due to a higher Bi-air surface tension.



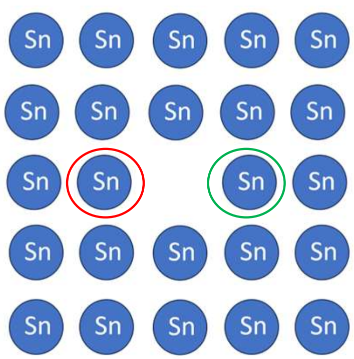


Agenda

- Diffusion and electromigration physics
- Ways of studying electromigration
- **Planar solder approach to studying Sn-Bi alloys**
  - Physics of solder resistance decrease under low temp and low current density.
  - Effect of Sn-Bi solder alloy composition
  - Arrhenius plots of electromigration rates
- **BTC solder approach to studying SAC305 alloy**
  - Physics of solder resistance decrease in the early stage of electromigration
  - Arrhenius plots of electromigration rates

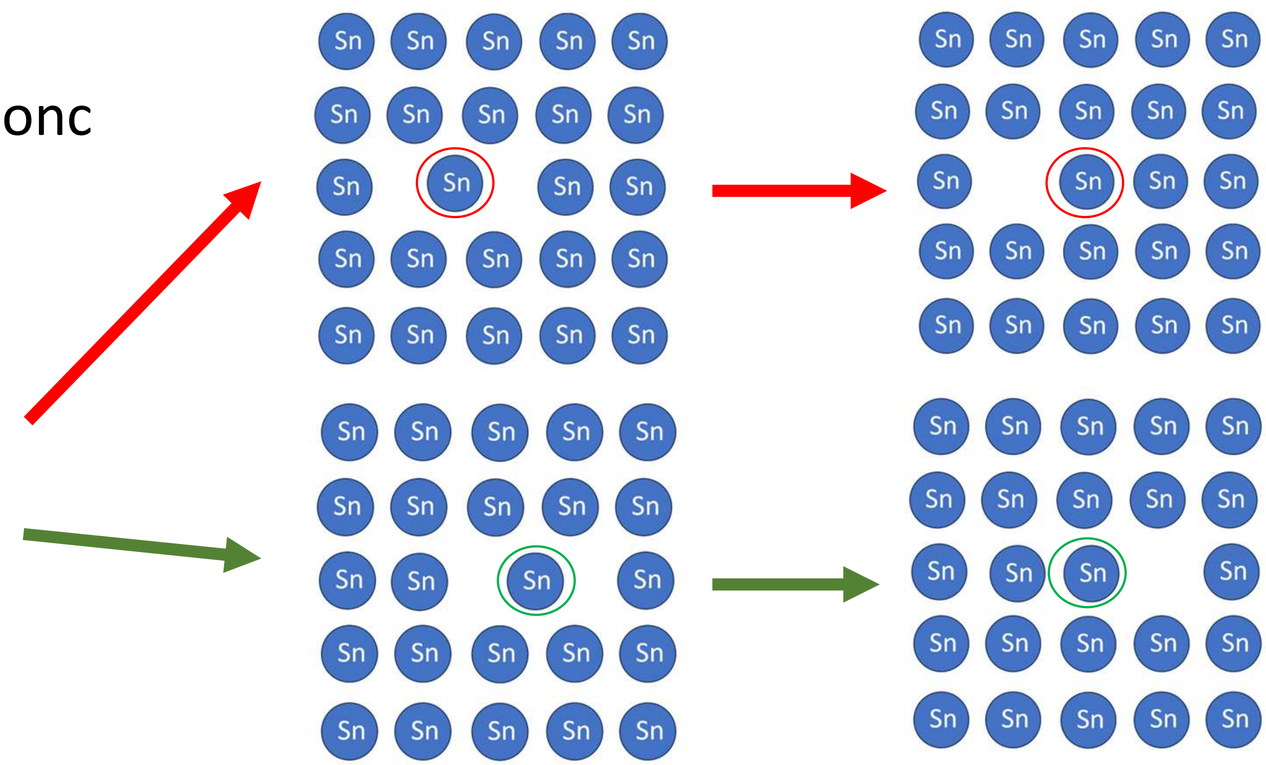
Diffusion in pure Sn is a random motion of atoms

Lattice vibration causes vacancy conc as a function of temperature



A Sn atom goes through a mid-point on its way to a neighboring vacant position.

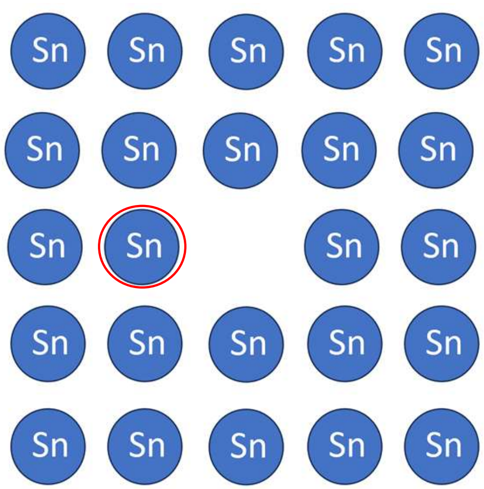
From its position at a mid-point, a Sn atom can randomly jumb either way, left or right.

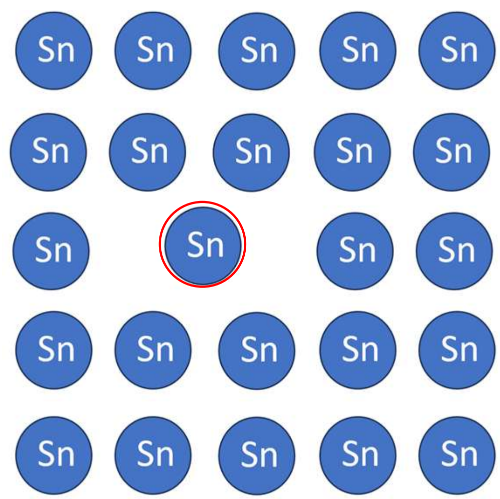


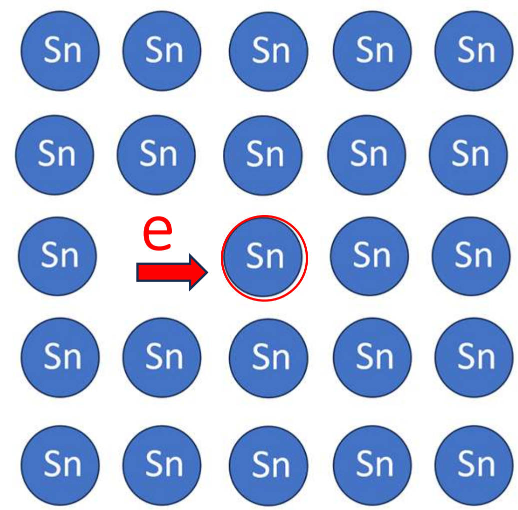
Electromigration in pure Sn is atomic diffusion biased in the direction of electron flow

Lattice vibration causes vacancy conc as a function of temperature

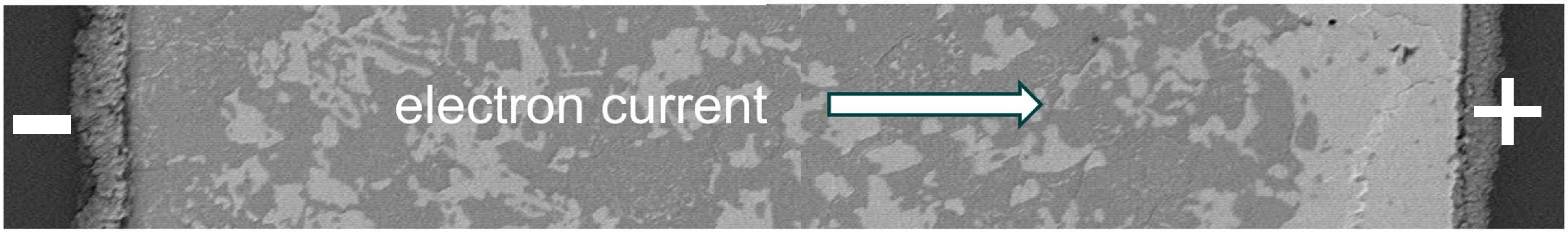
A Sn atom's jump into a vacancy is biased in the direction of electron flow







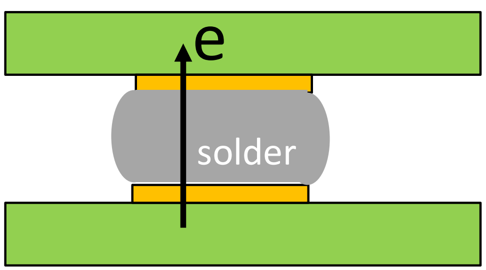
Electromigration in tin-bismuth (Sn-Bi) solder 35 μm thick



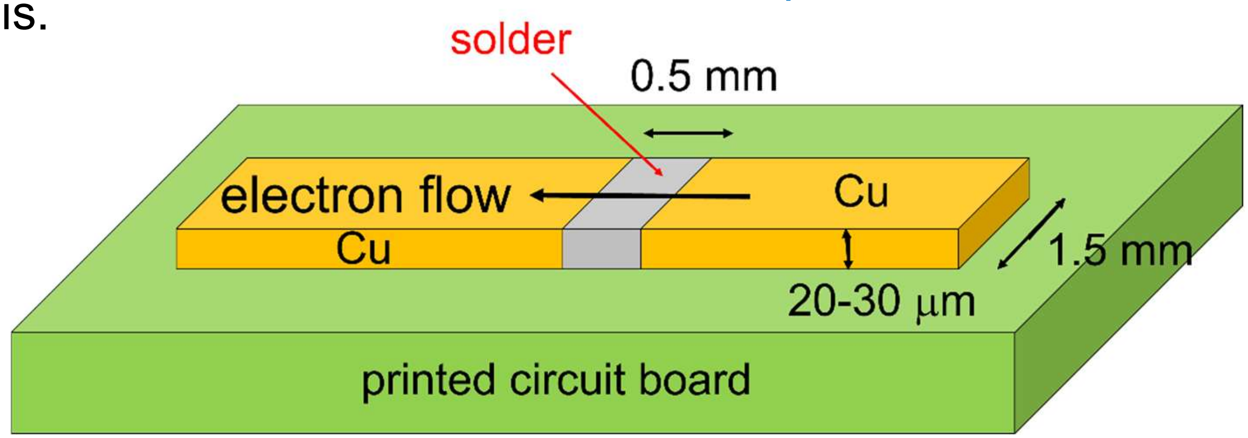
Electrons have mass and velocity and therefore momentum.
Newton proved that momentum is conserved when objects collide.
Electrons collide with and transfer momentum to atoms, preferentially Bi atoms in case of Sn-Bi alloys.
Bi atoms drift in the direction of electron current, piling up at the positive (anode) end of the solder as a Bi-rich phase.
Because Bi phase is more resistive, solder joint resistance rises.

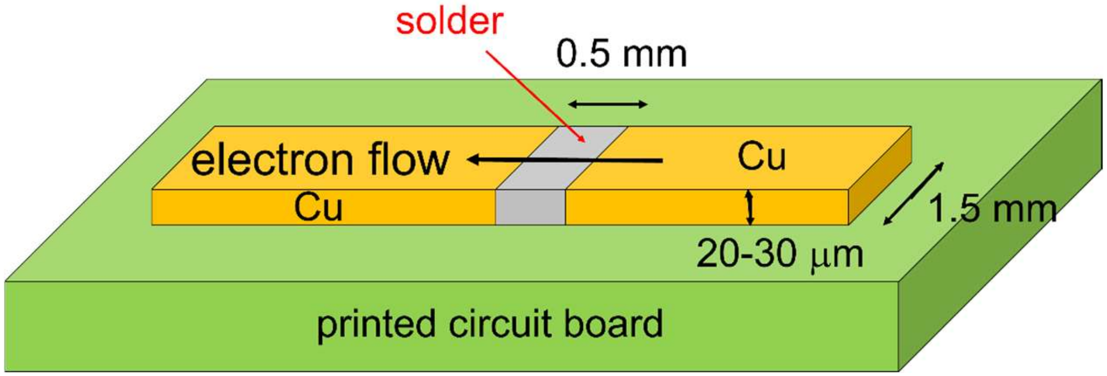
Ways to study electromigration in solder joints

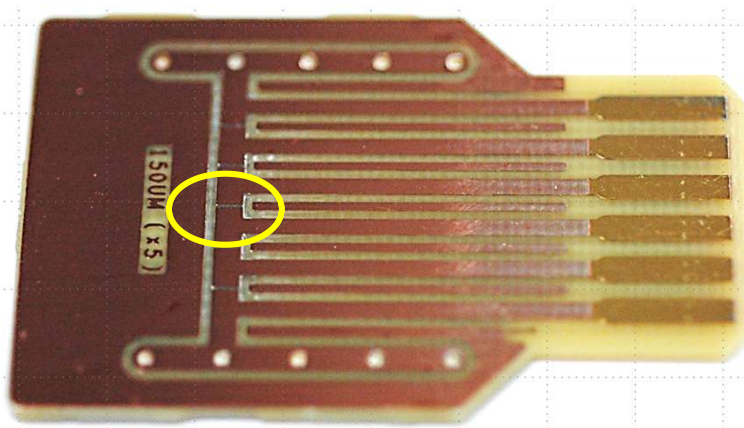
- **Study solder joints as in actual products.**
- **Resistance is the only means to track electromigration**
- Observing Bi segregation involves destructive analysis.

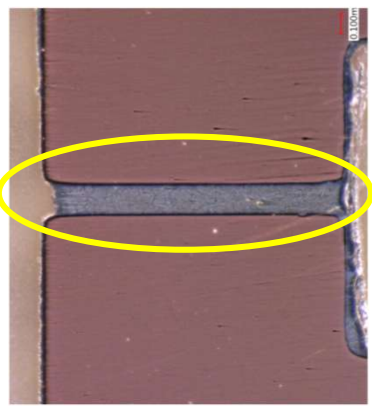


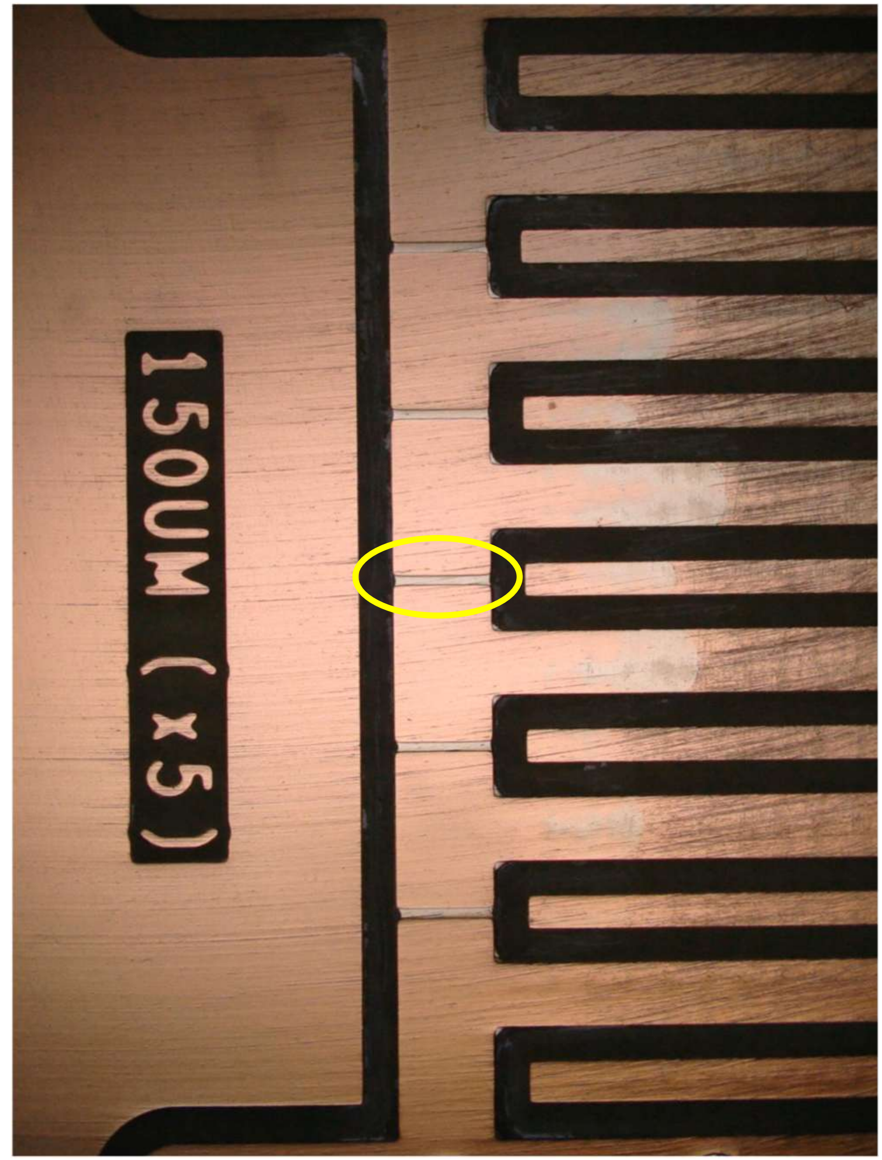
- **Study solder joints in rectangular prism shape we call planar joints.**
- Microstructural changes and electromigration can be tracked non-destructively while monitoring the resistance of the solder specimens.







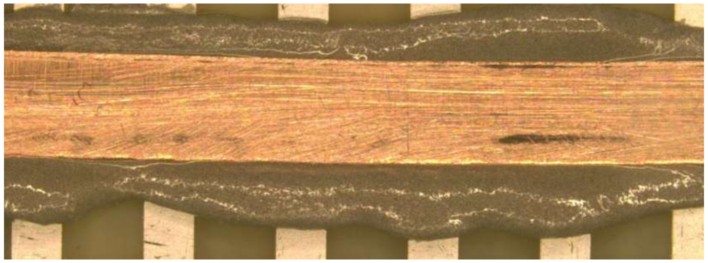




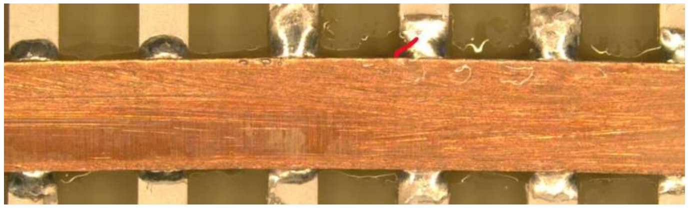
The solder planar specimens were 1.5-mm wde, 0.2- to 0.4-mm long and 35-μm thick.

Fabricating Sn-Bi planar solder joints

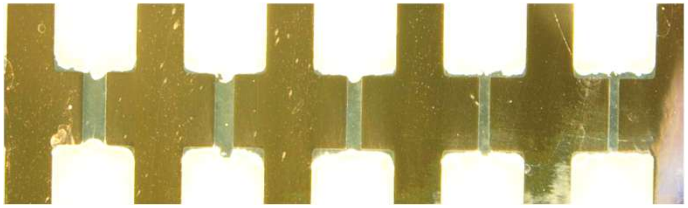
Spread solder paste and cover with copper strip 1.5-mm wide and 0.1-mm thick



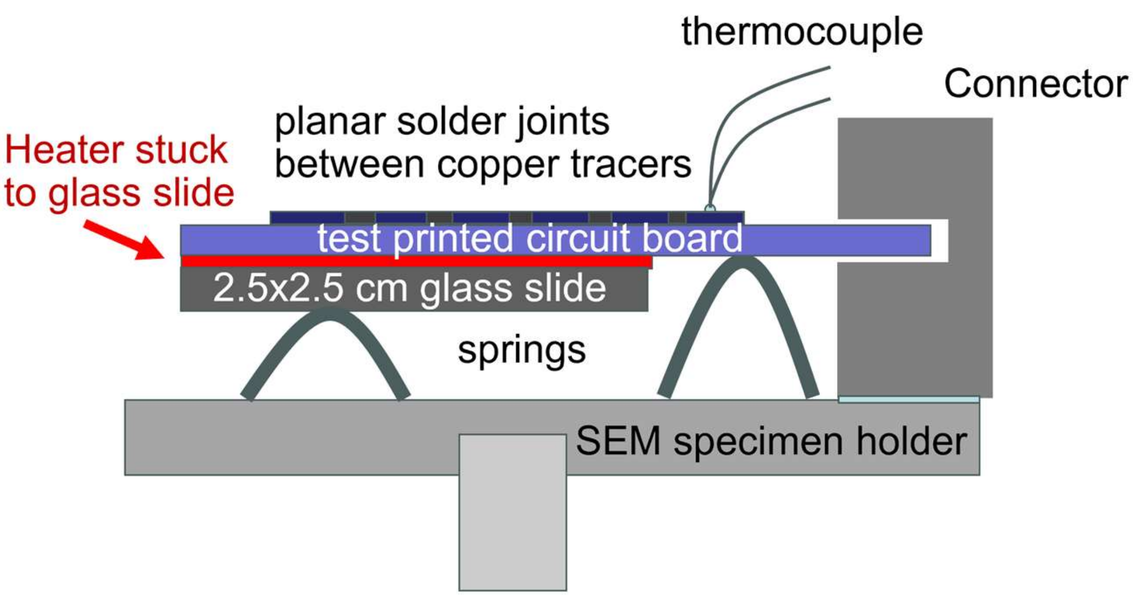
Reflow solder at 180 °C for 12 minutes

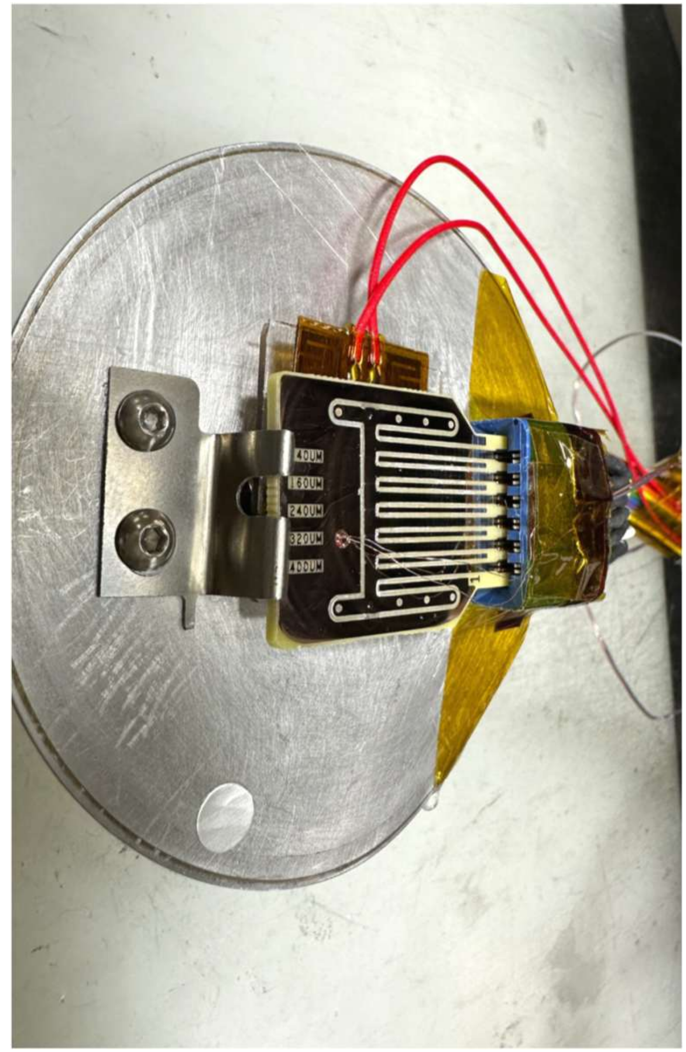


Peel off the copper strip, grind and then polish with 1-μm diamond paste.

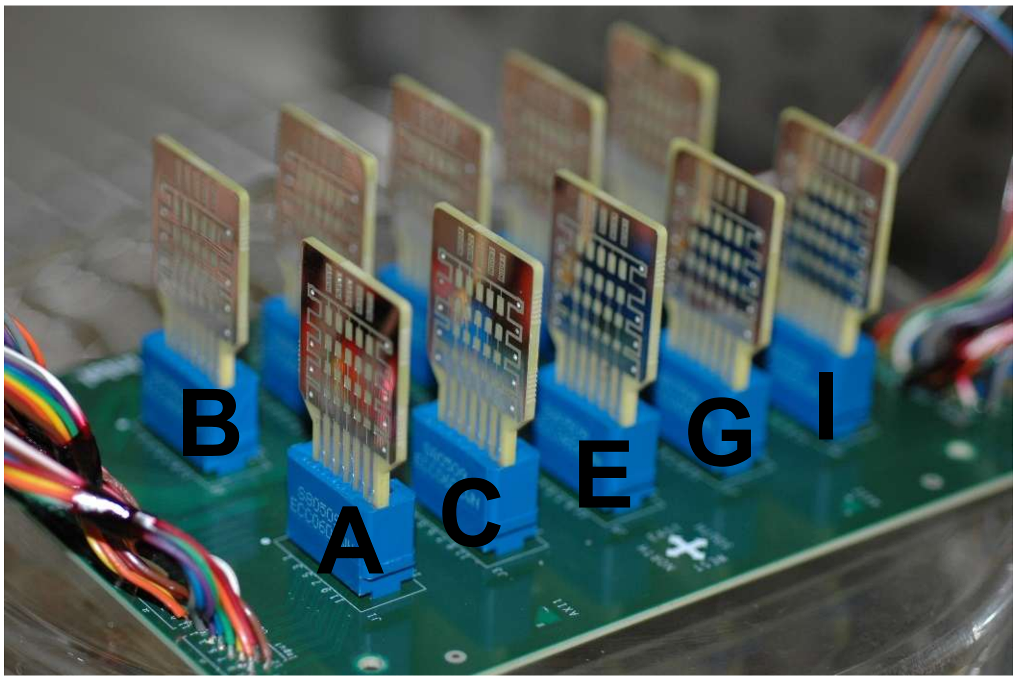


Homemade hot stage for SEM study of planar solder joints

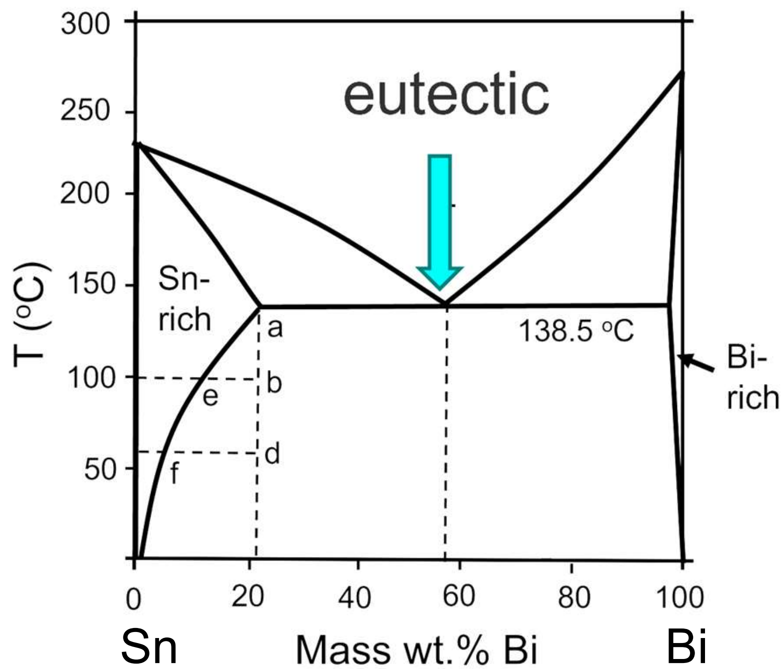


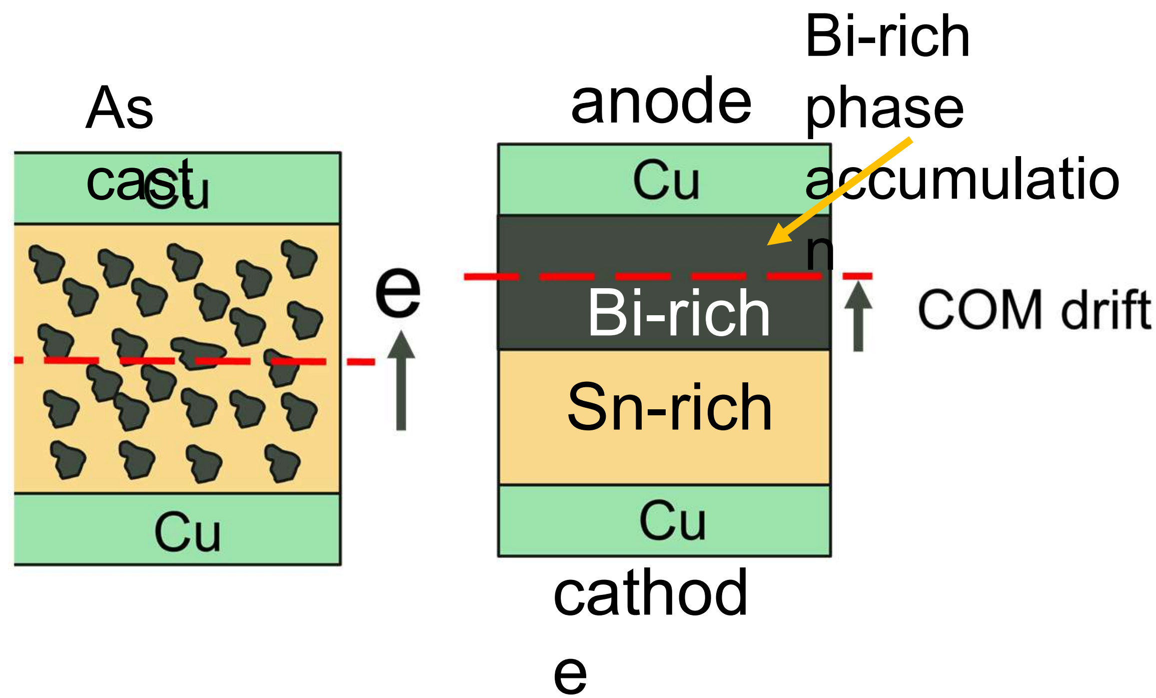


Electromigration test setup for planar solder joints



Electromigration in eutectic Sn-Bi (58 wt.% Sn, 42 wt.%Bi) solder

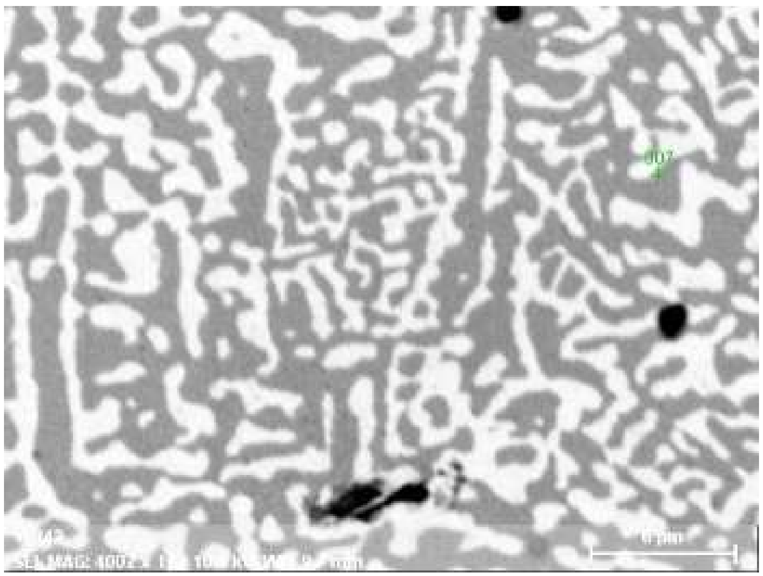




The Bi-rich phase particles migrate to and collect at the anode interface.
COM ≡ center of mass

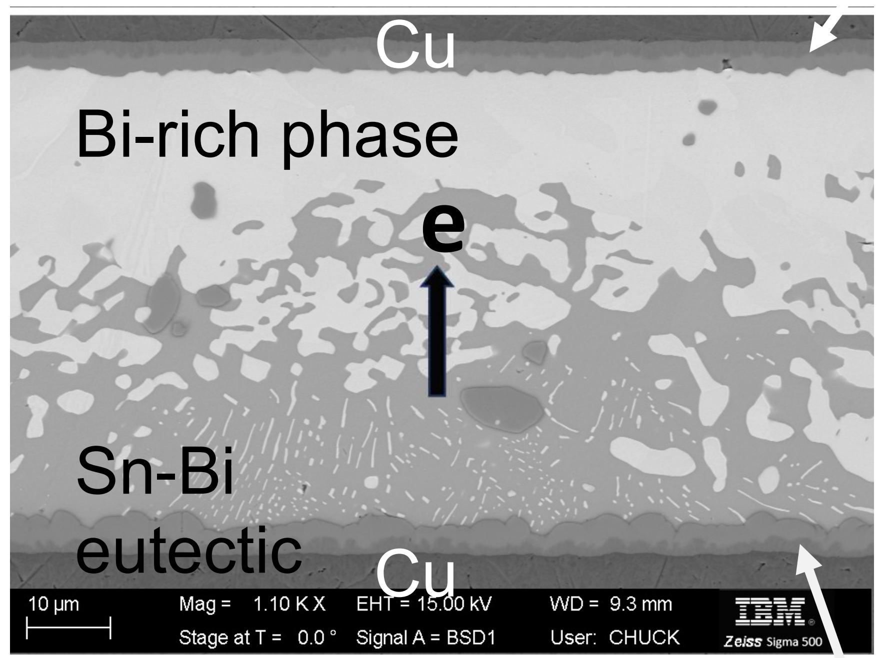
Electromigration in eutectic Sn-Bi (57 % Sn, 43 %Bi)

Thermal aging



Electromigraiton

Cu-Sn IMC

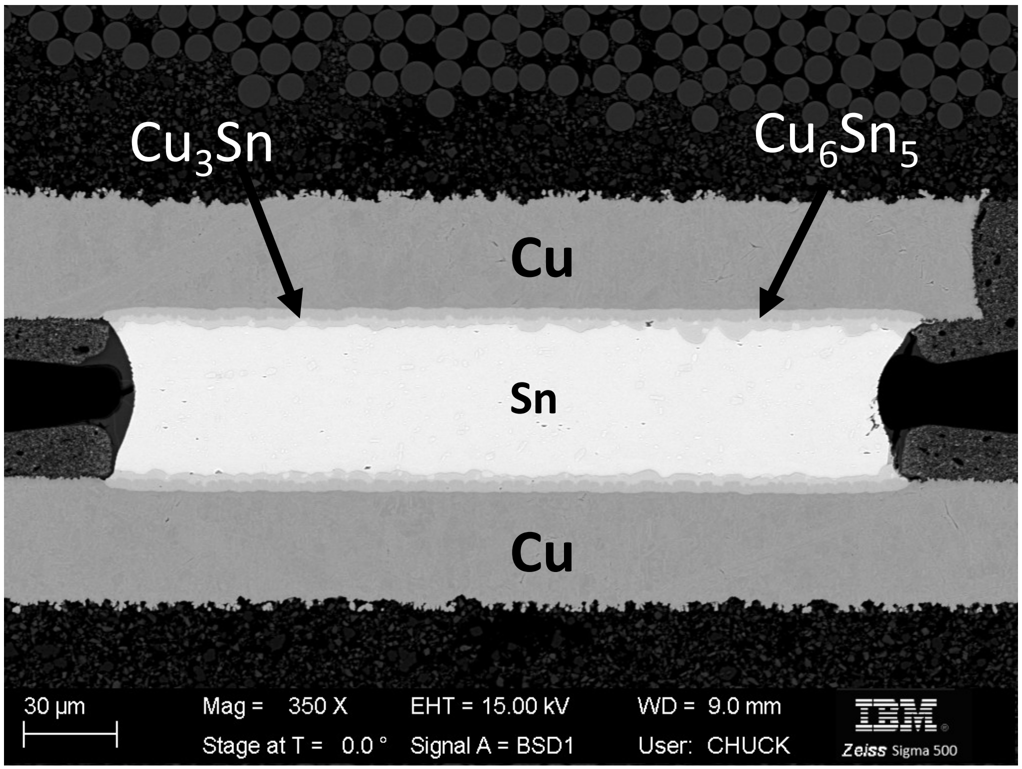


Cu-Sn IMC

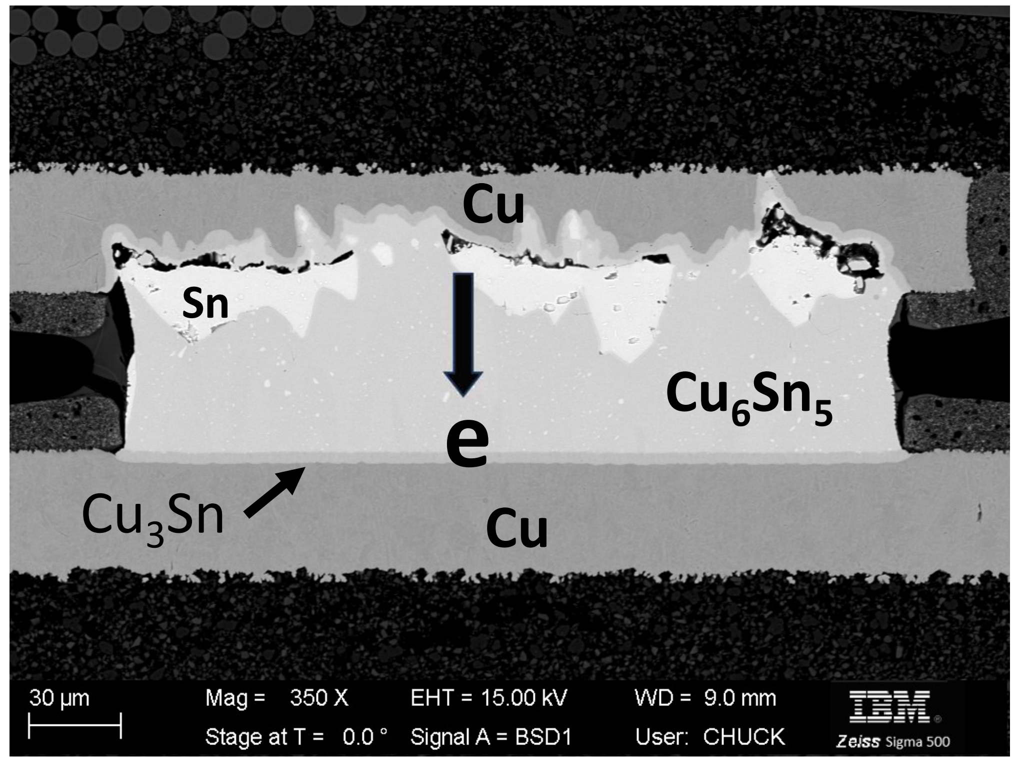
Why does copper not migrate fast in the Sn-rich phase here as it does in SAC305 solder forming a thick layer of Cu_6Sn_5 at the anode?

Electromigration in SAC305 (Sn, 3 wt.% Ag, 0.5 wt.% Cu) solder

Thermal aging (90-125 °C)

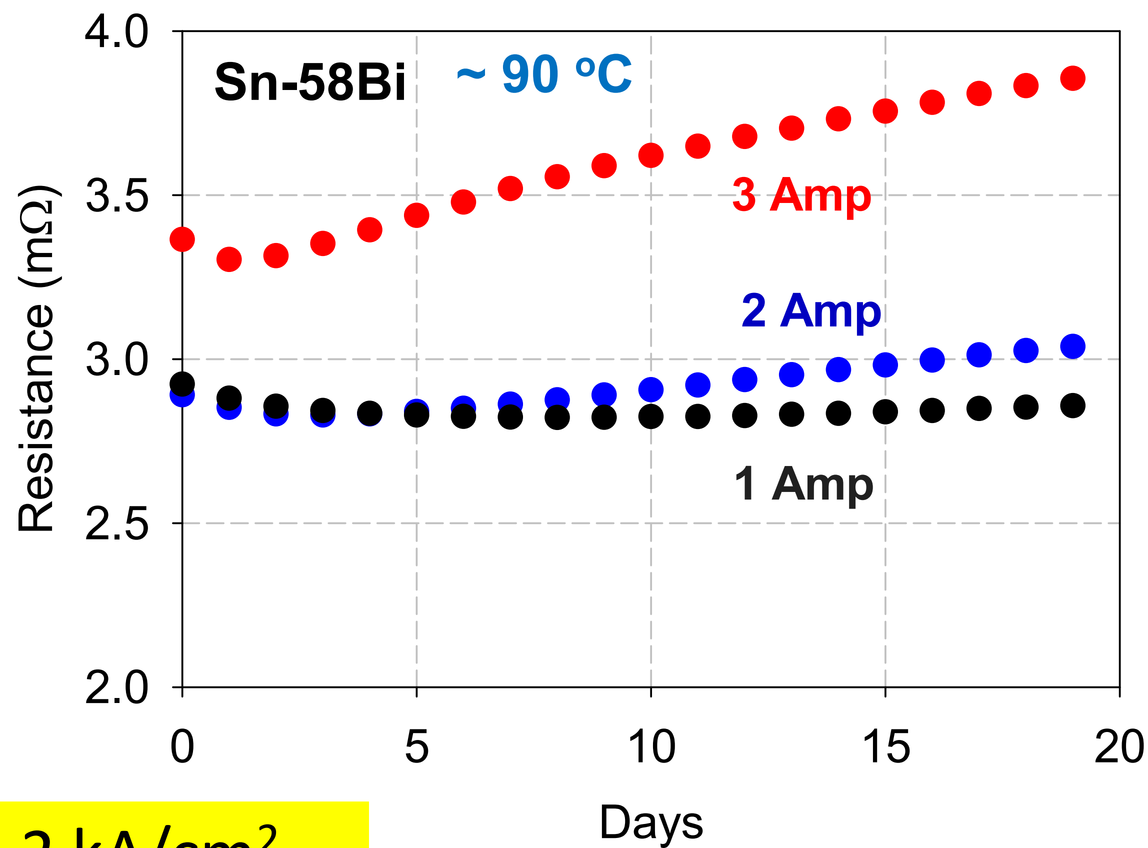


Electromigration



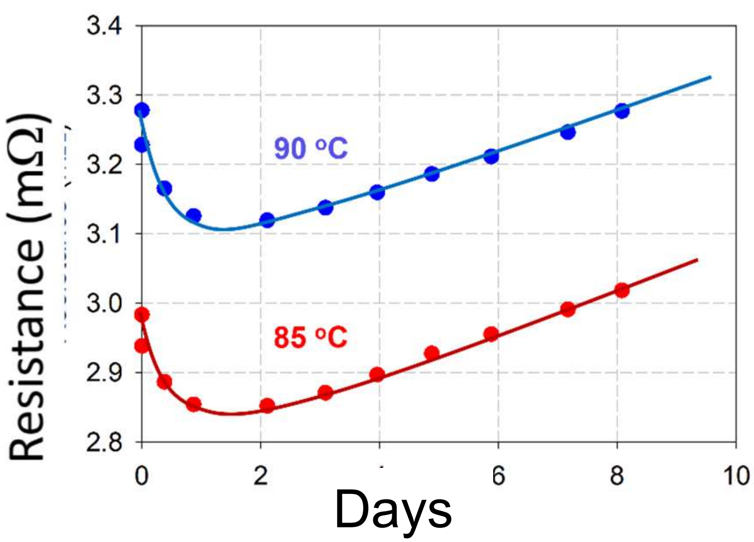
Cu is an interstitial fast diffuser in Sn. Cu reacts with Sn forming Cu_6Sn_5.

Why does the Sn-Bi planar solder joint resistance decrease with time at lower temperatures and current densities?



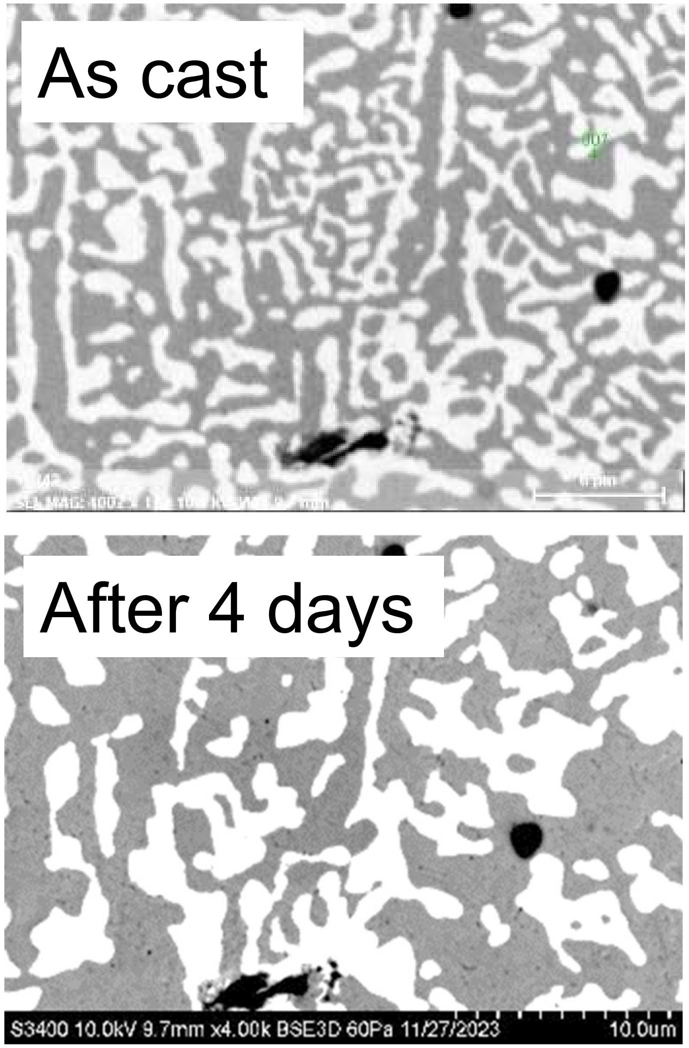
1 Amp = 1/(0.15x0.003) = 2.2 kA/cm^2

Microstructural coarsening causes the dip in resistance

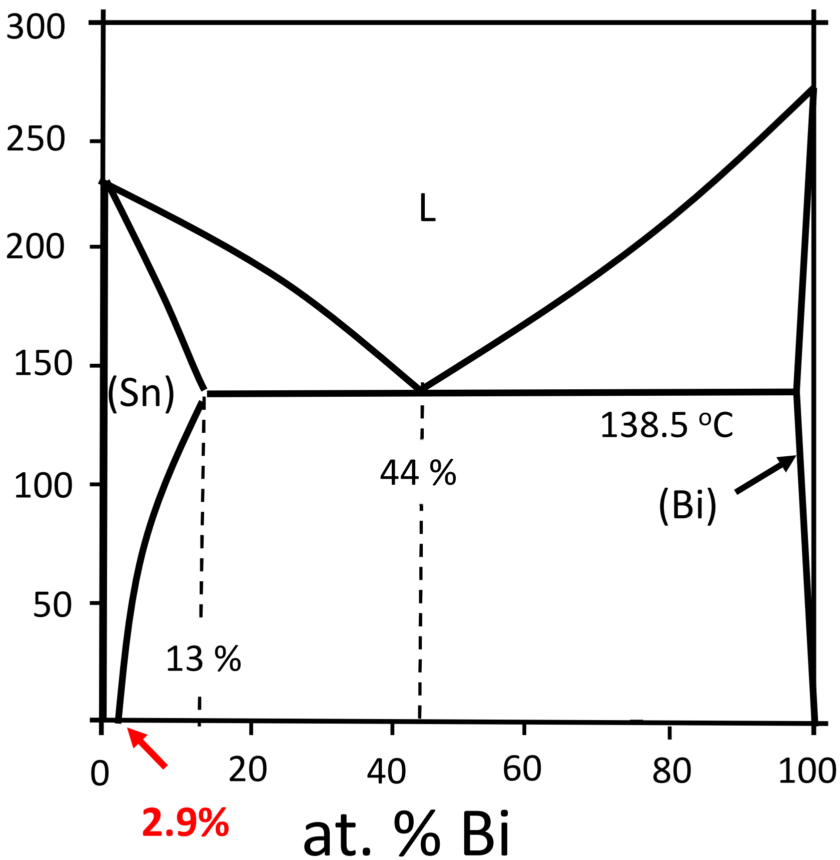


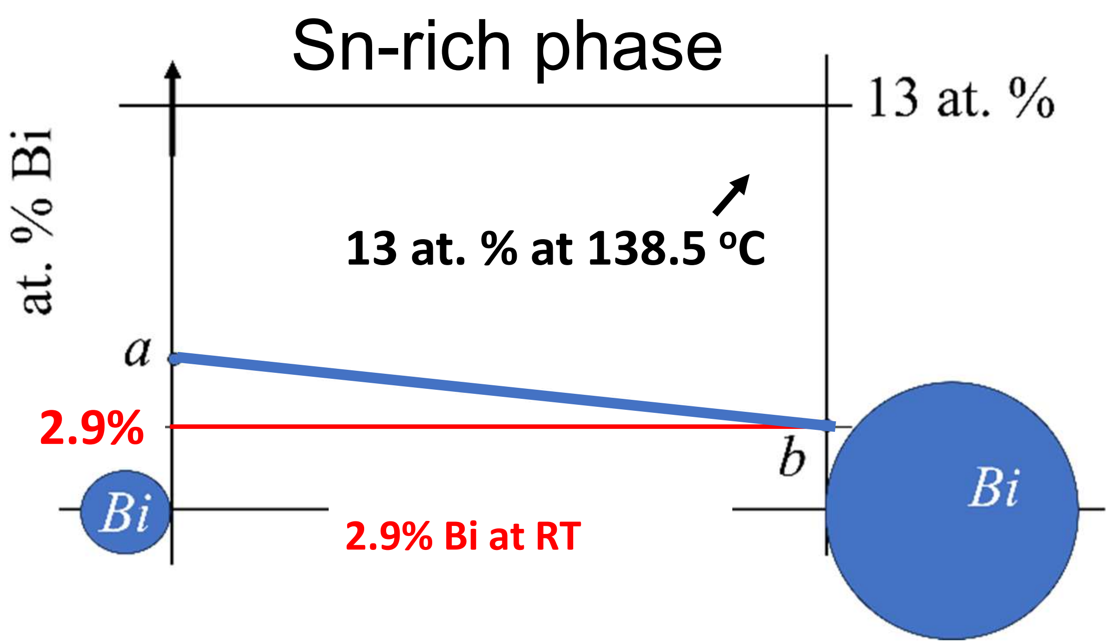
The Sn-rich phase matrix (darker phase) is the less resistive phase and therefore the preferred path for current flow.

4.4 kA/cm^2 at 90 °C



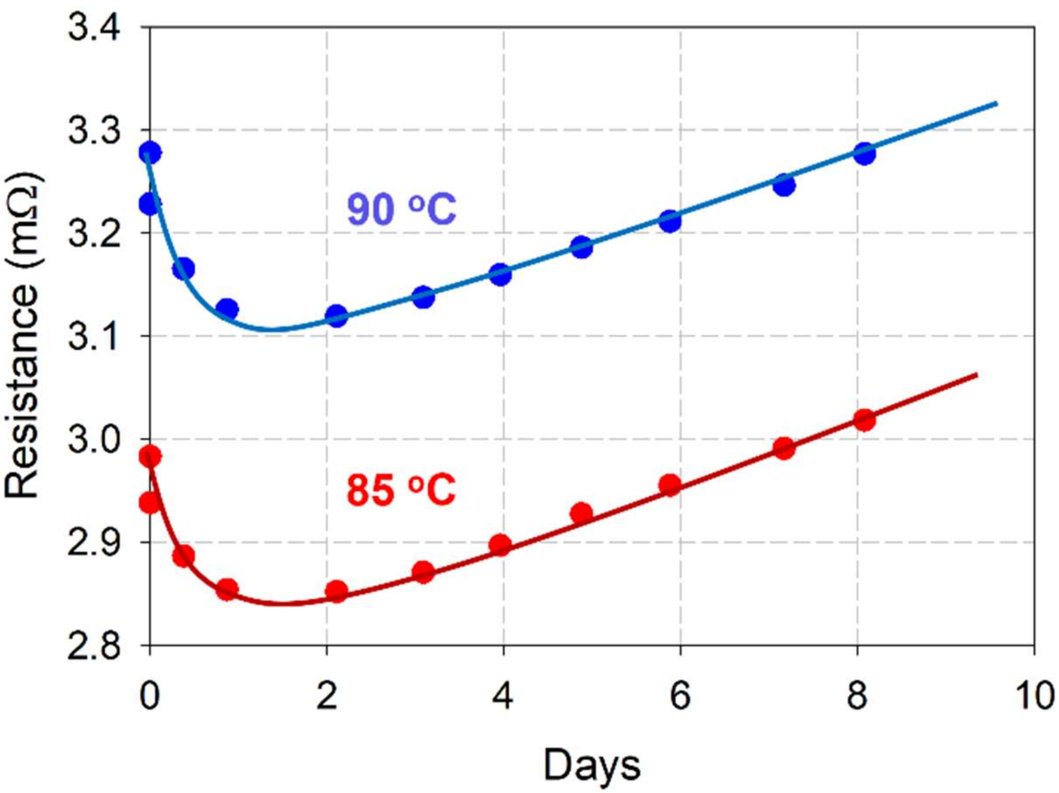
Ostwalt ripening: Larger Bi particles grow and smaller ones dissolve



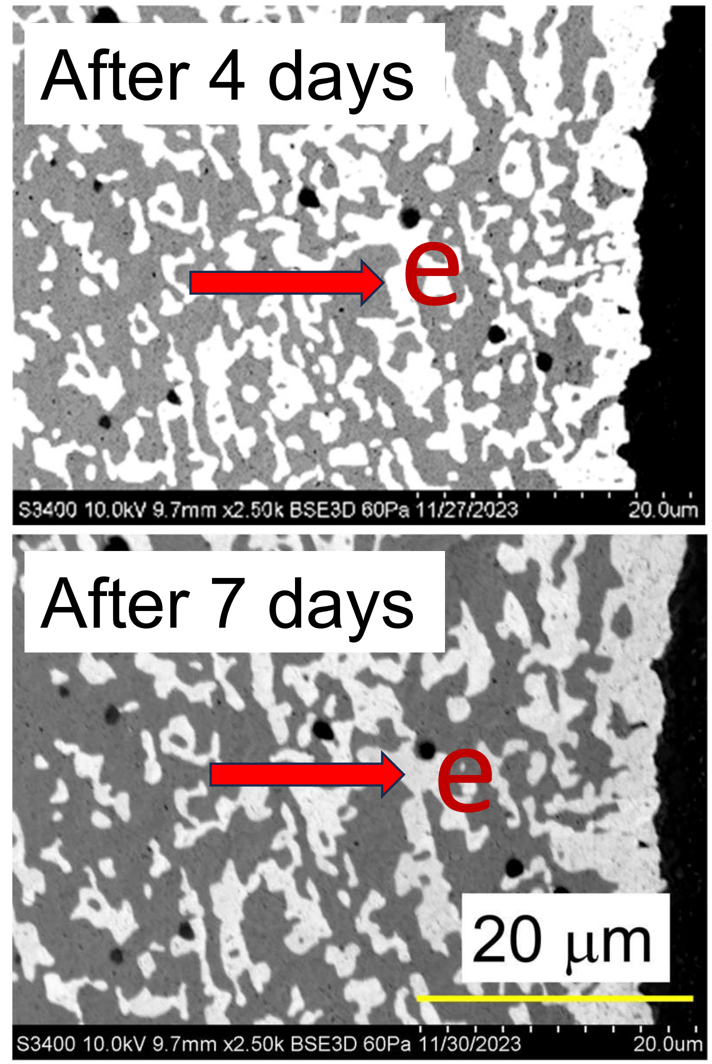


Do phase diagrams depend on the phase particle sizes?

Bismuth accumulation at the anode causes the rise in resistance

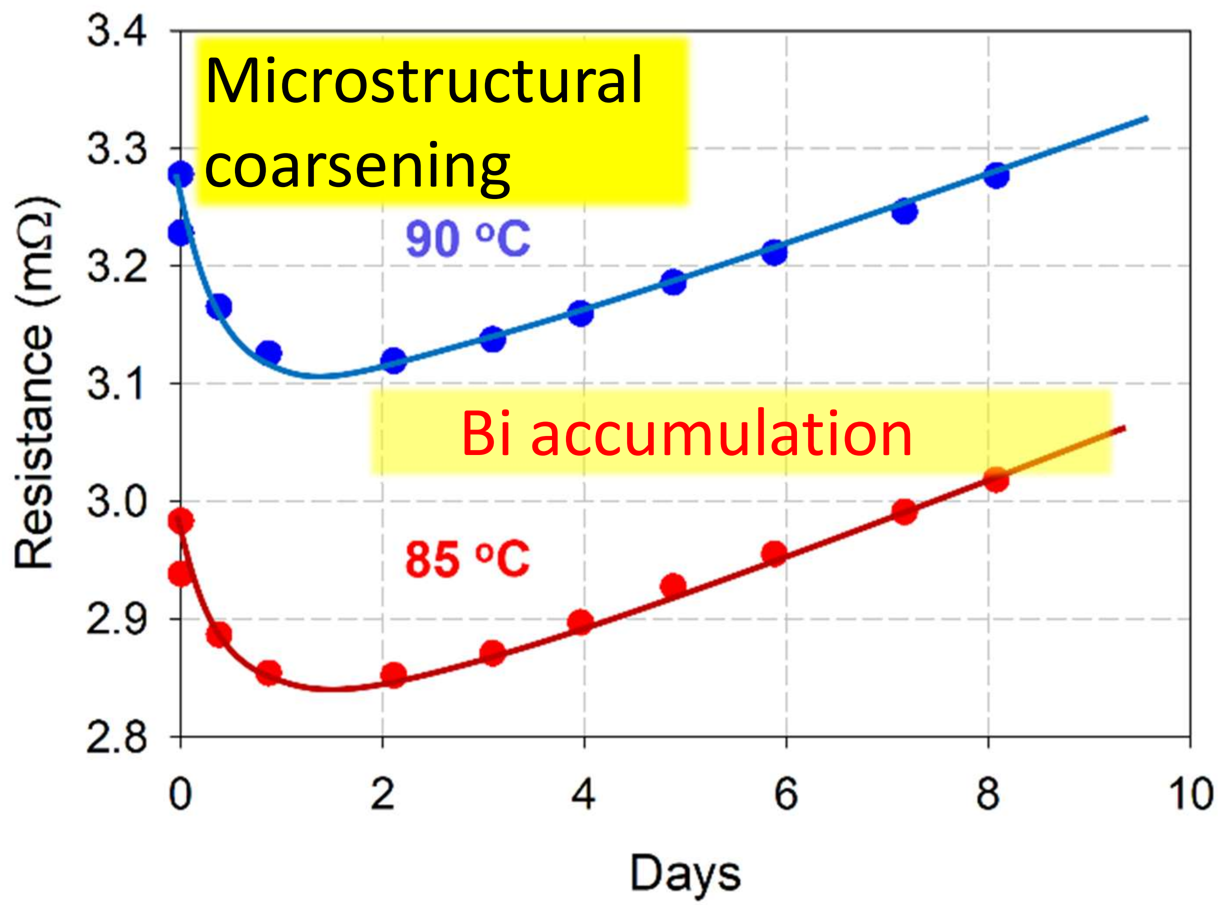


4.4 kA/cm^2 at 90 °C



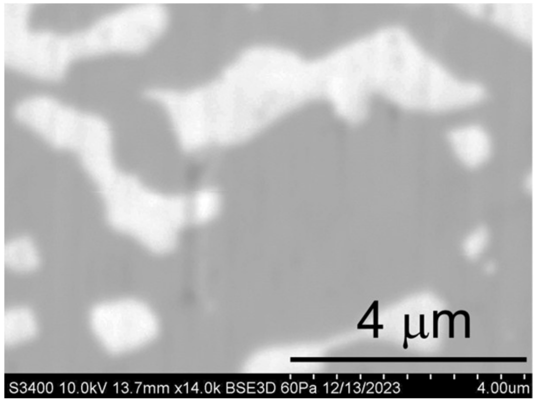
Microstructural coarsening and bismuth accumulation

Microstructural coarsening lowers joint resistance.
Bi accumulation raises joint resistance

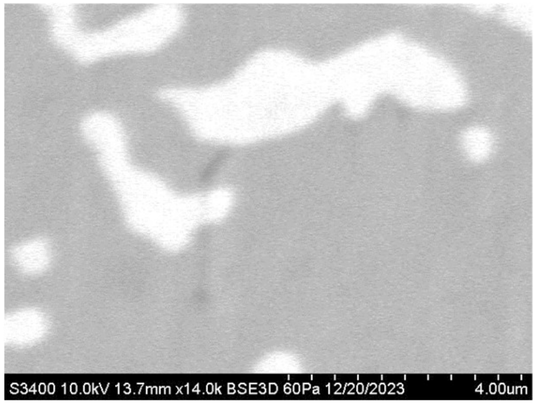


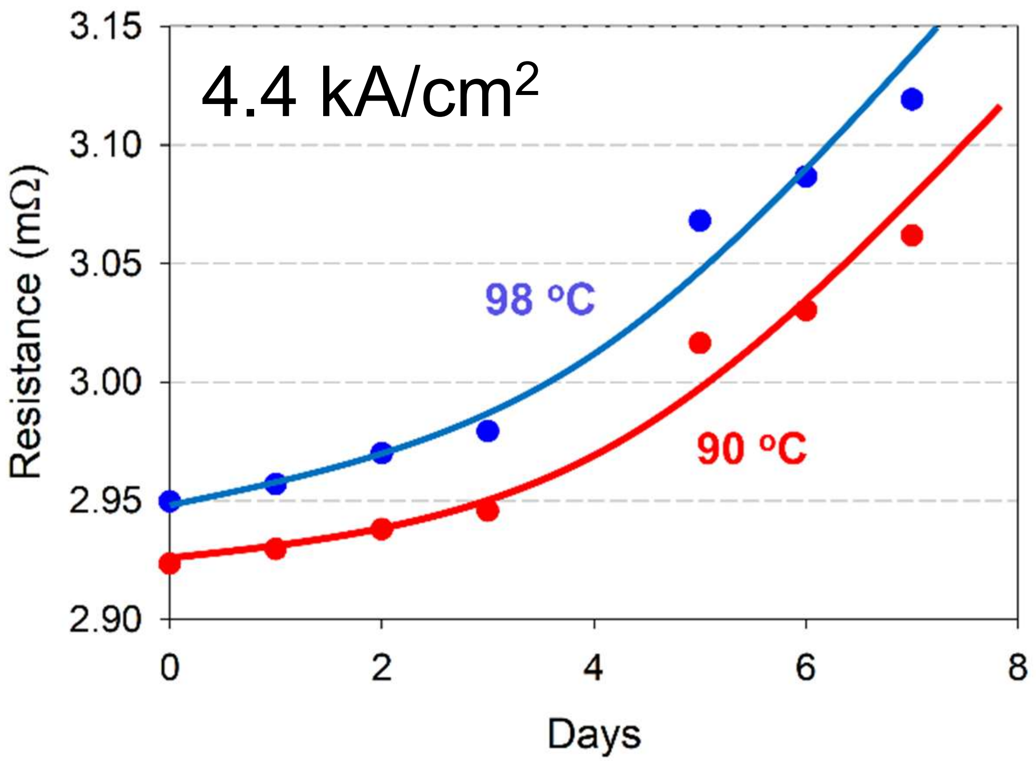
What if we started with a coarse microstructure in which the bismuth particles could not grow?

At start



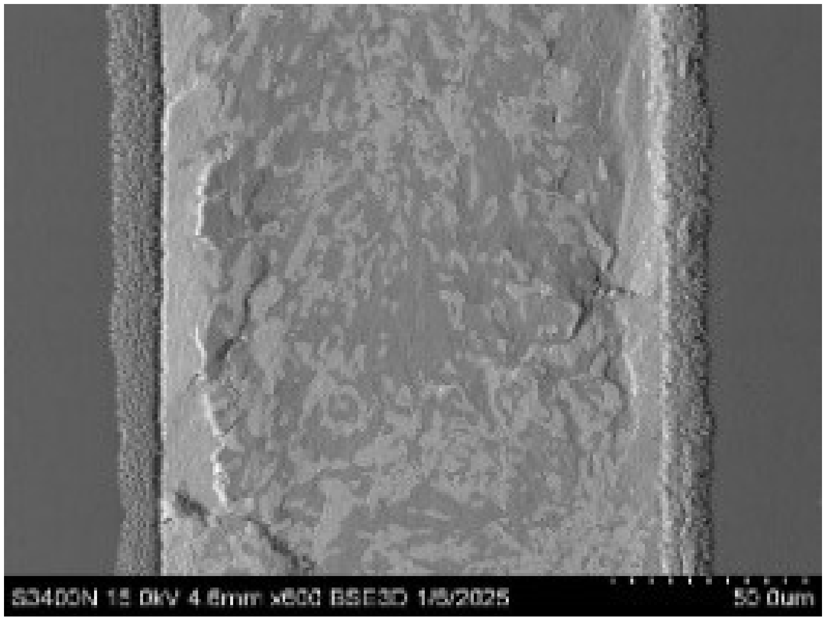
After 4 days



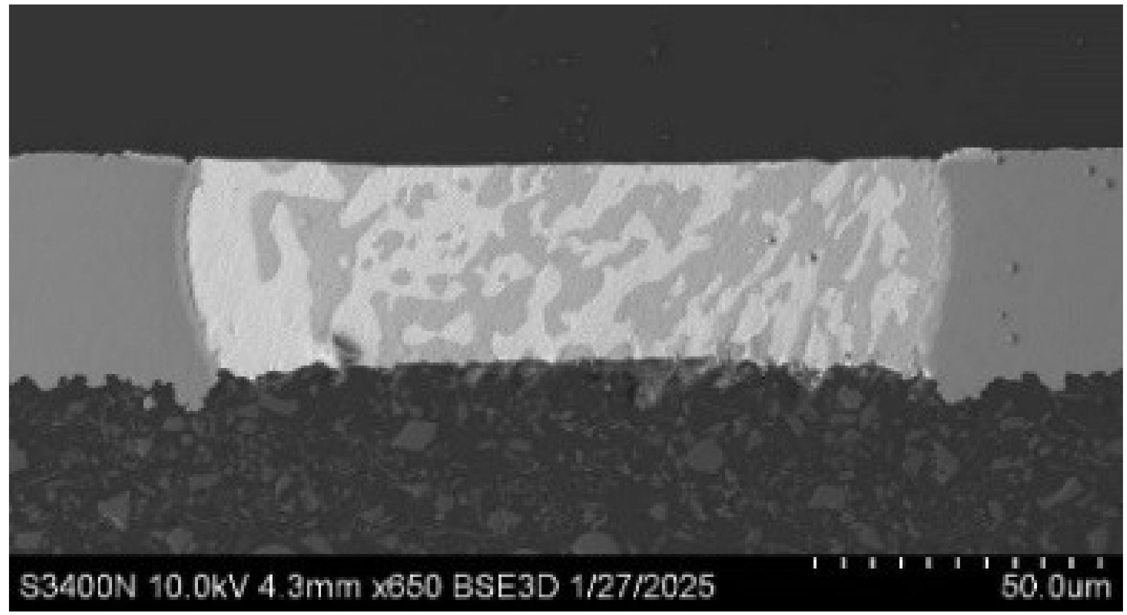


Studying the effect of Sn-Bi alloy composition on electromigration rate using the planar solder approach

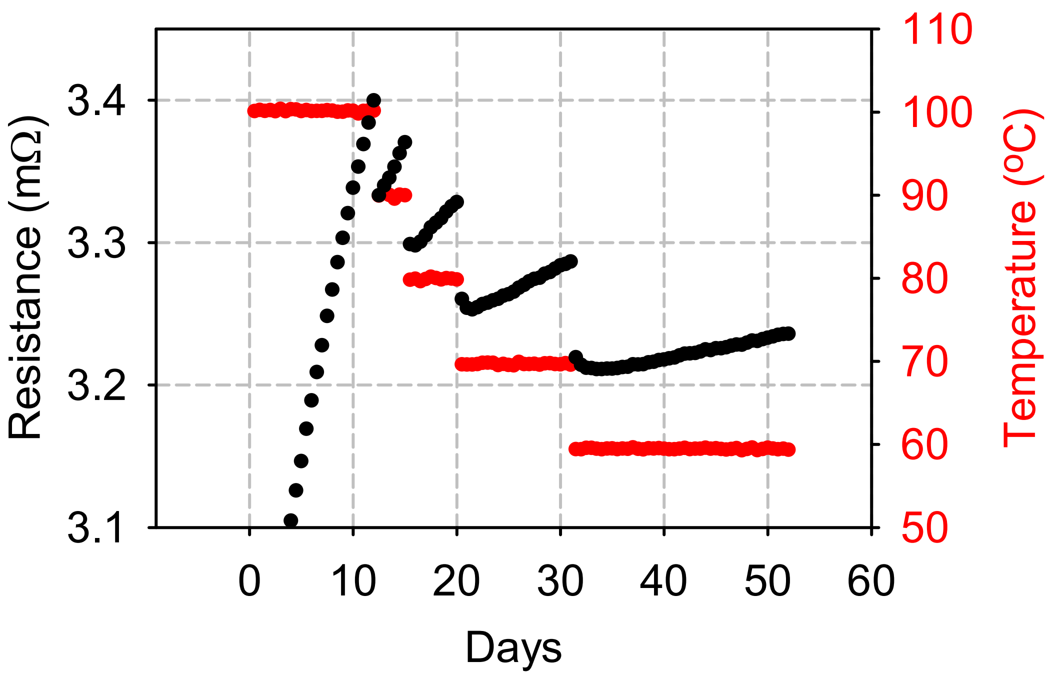
Anode Cathode

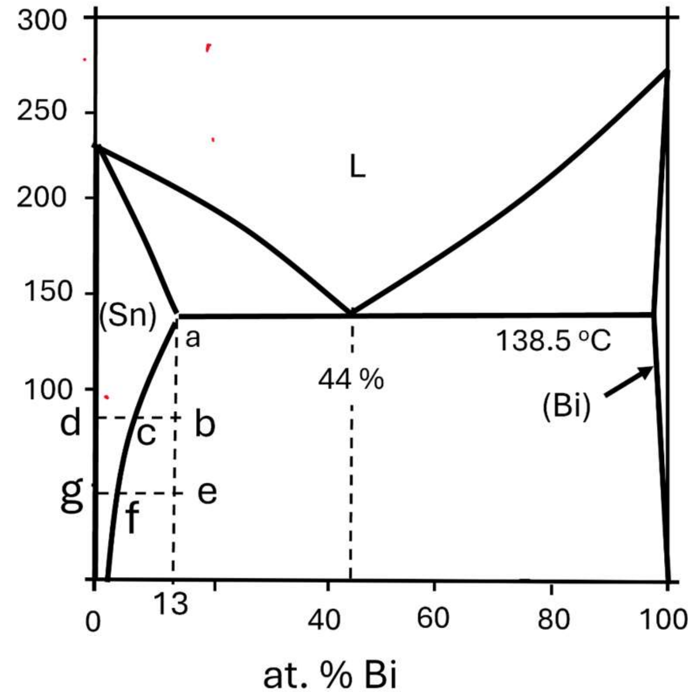


Anode Cathode



The bright phase is the Bi-rich phase that electromigrates towards the anode and causes the solder joint resistance to rise and make the joint brittle.

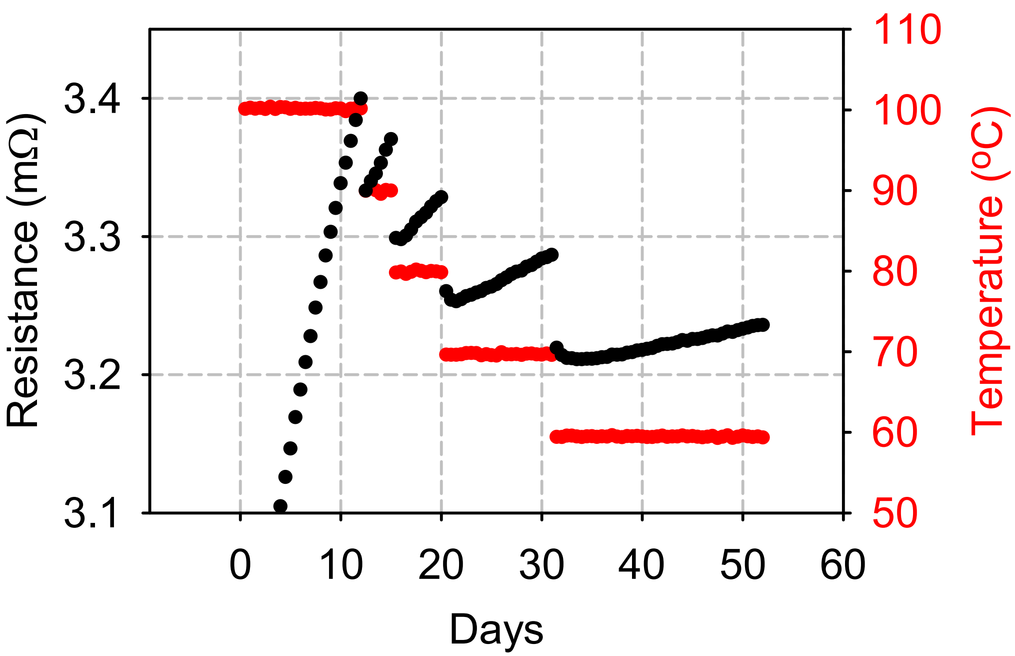


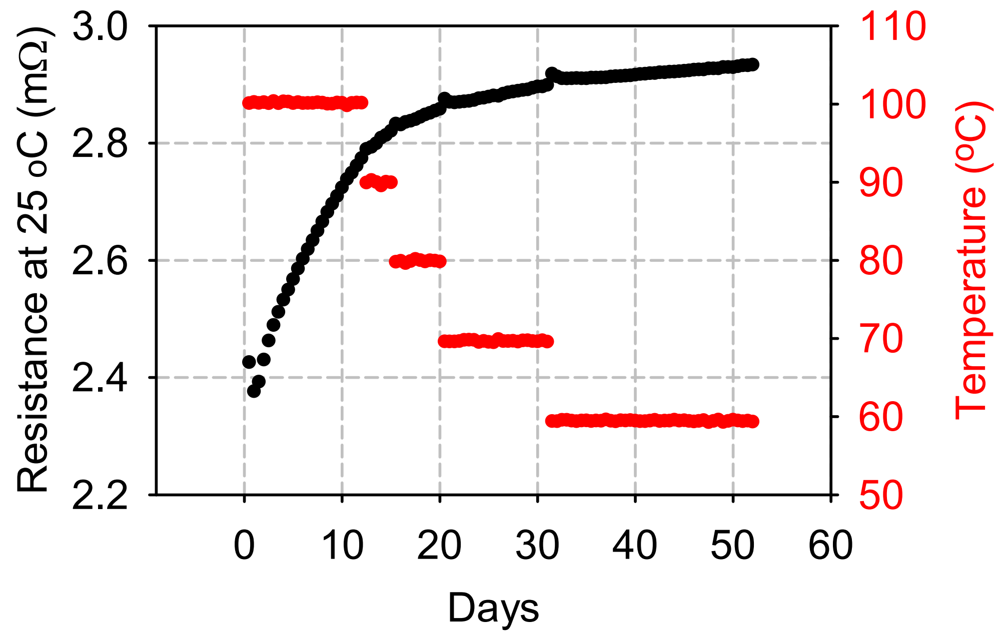


The jog in the R vs t curve is due to temp coeff of resistance..
The dip in the curve is due to the Sn-rich becoming purer (its Bi content decreasing).

Normalization of joint resistance so that we can use joint resistance as a measure of EM

$$R_{25} = \frac{R_1}{1+\alpha\left(T_1 - 25\right)}$$





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

Electric field = force/charge

Force = (electric field)(charge)

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

Assuming $v \propto$ rate of change of resistance

$$v \propto \frac{\Delta R}{\Delta t} = \frac{\Delta R}{days}$$

$$\frac{\left(\Delta R/days\right)T}{j} \propto \frac{D_0 Z^{*}e\rho}{k} e^{-\frac{Q}{kT}}$$

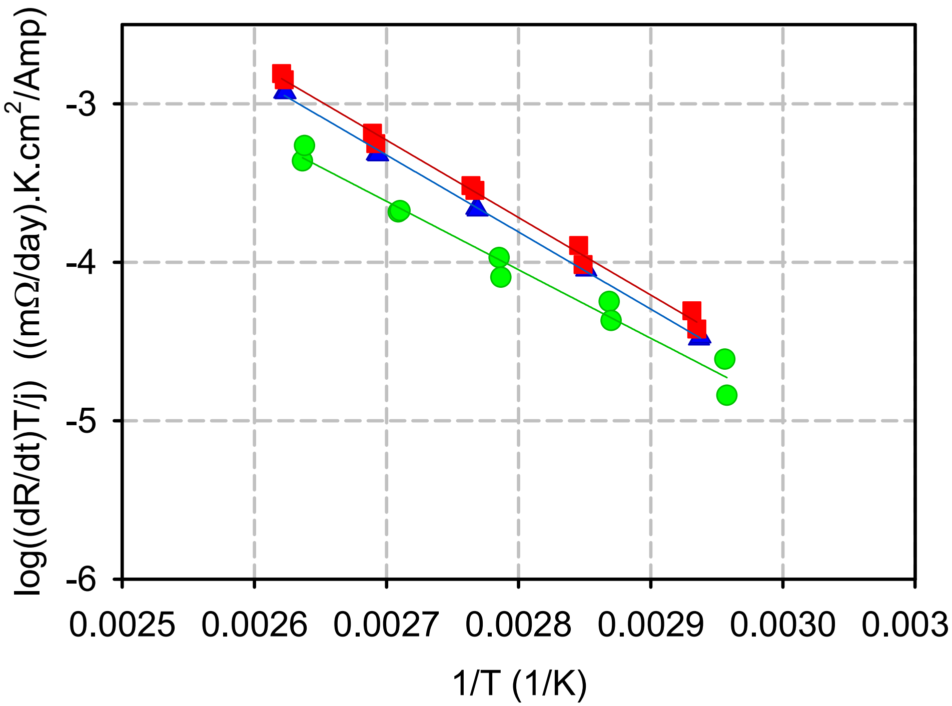
$$\log \frac{\left(\Delta R/days\right)T}{j} = A - \frac{Q}{kT}$$

Run 2: #1=58Bi; #3=57Bi-1Ag; #9=40Bi-0.5Sb-0.03Ni

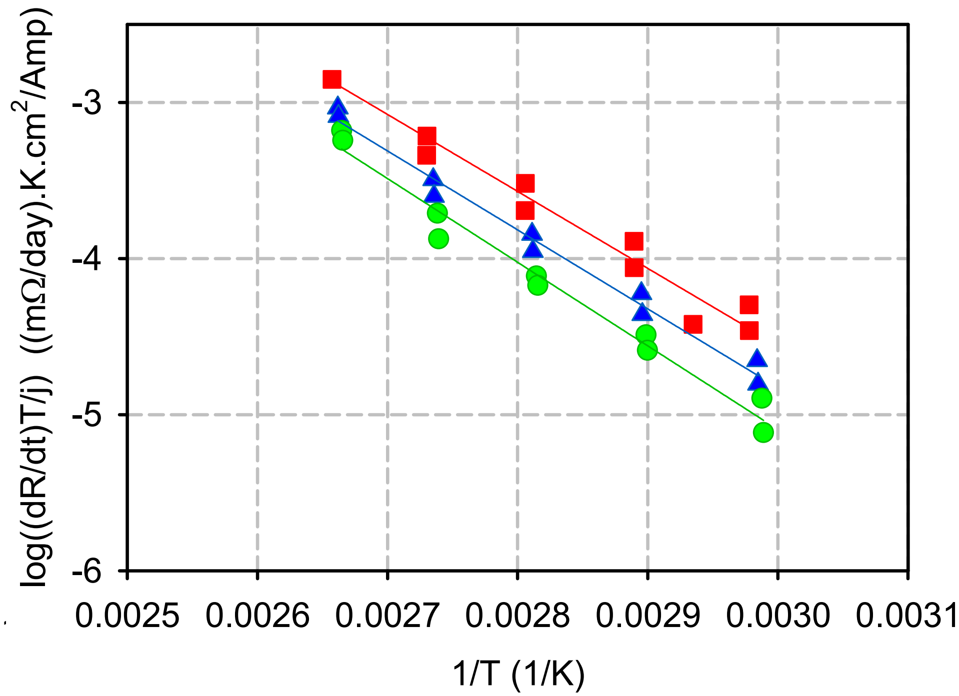
Ag addition increases EM.

Hypoeutectic Sn-Bi has lower EM.

3 Amp, 2nd run, planar
#1, pos 102 and 104 is blue triangle, Q=0.97 eV
#3, pos 107 and 109 is red square, Q=0.96 eV
#9, pos 112 and 114 is green circle, Q=0.86 eV

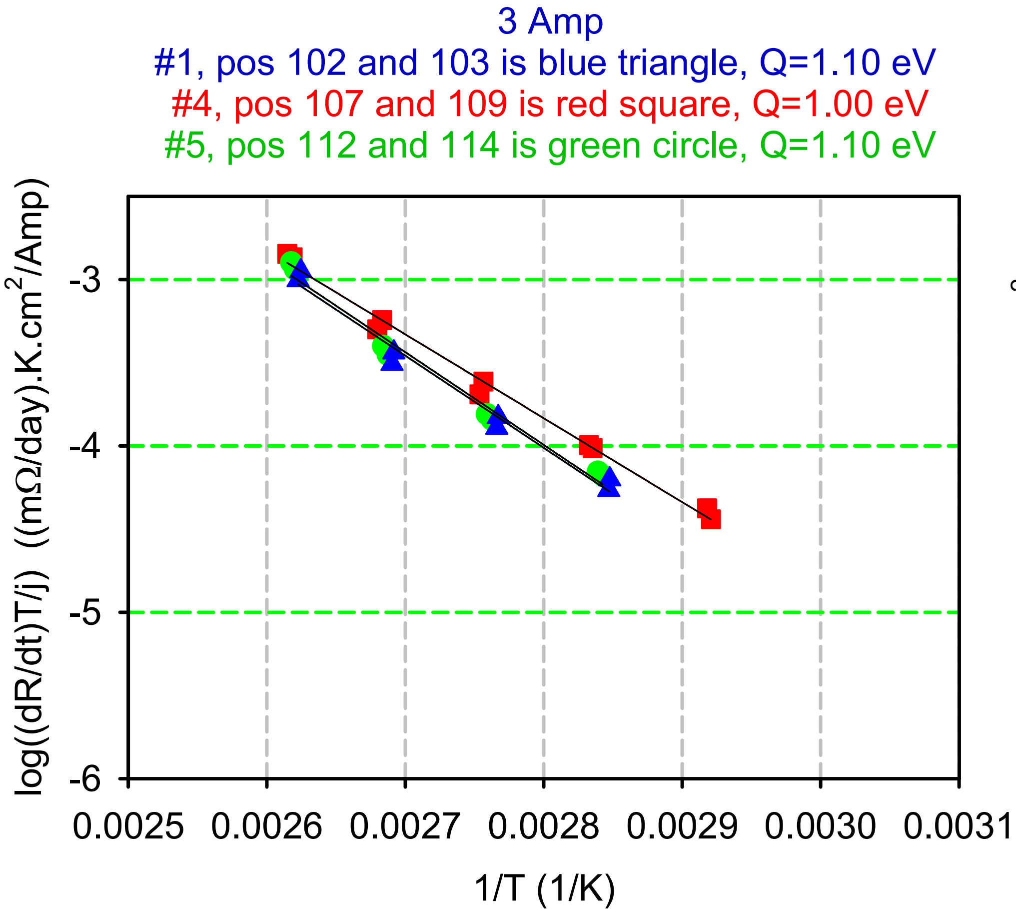


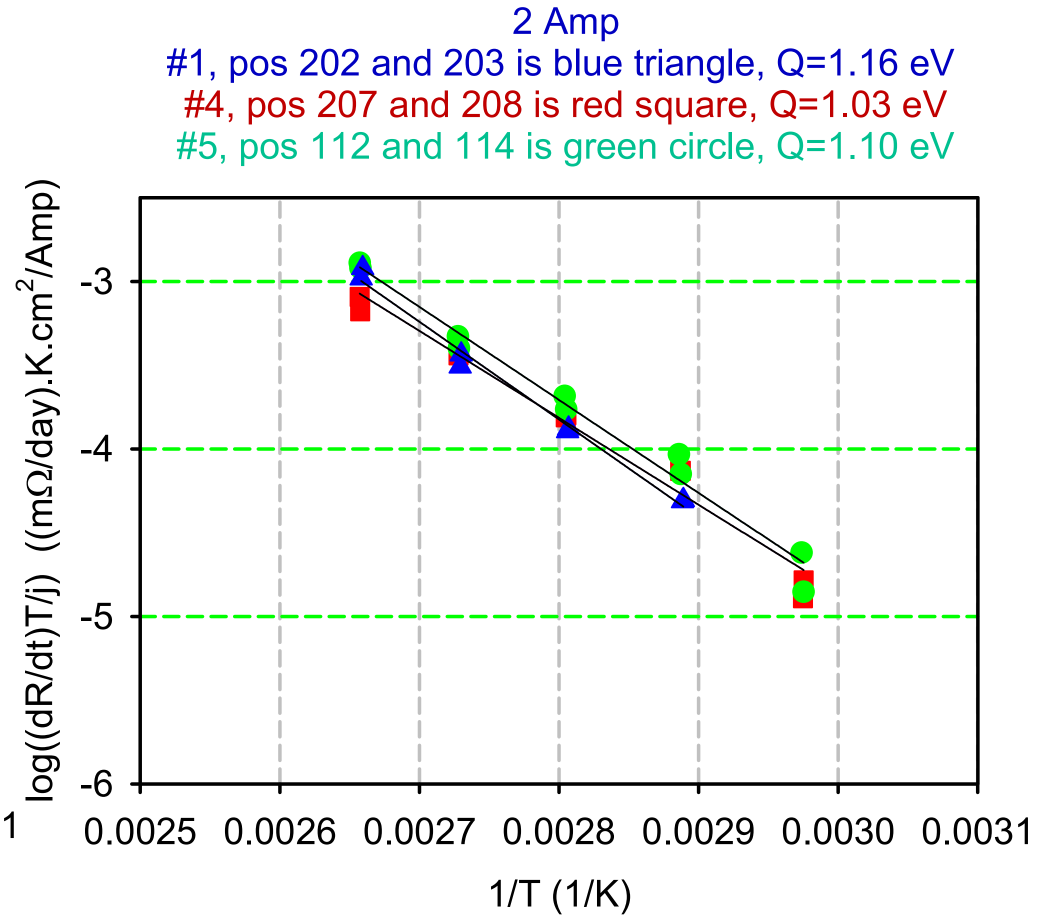
2 Amp. 2nd run, planar
#1, pos 102 and 104 is blue triangle, Q=0.98 eV
#3, pos 107 and 109 is red square, Q=1.00 eV
#9, pos 112 and 114 is green circle, Q=1.06 eV



Run 3: #1=58Bi; #4=57Bi-1Ag-0.5Sb; #5=57Bi-0.5Sb

Ag addition increases EM.

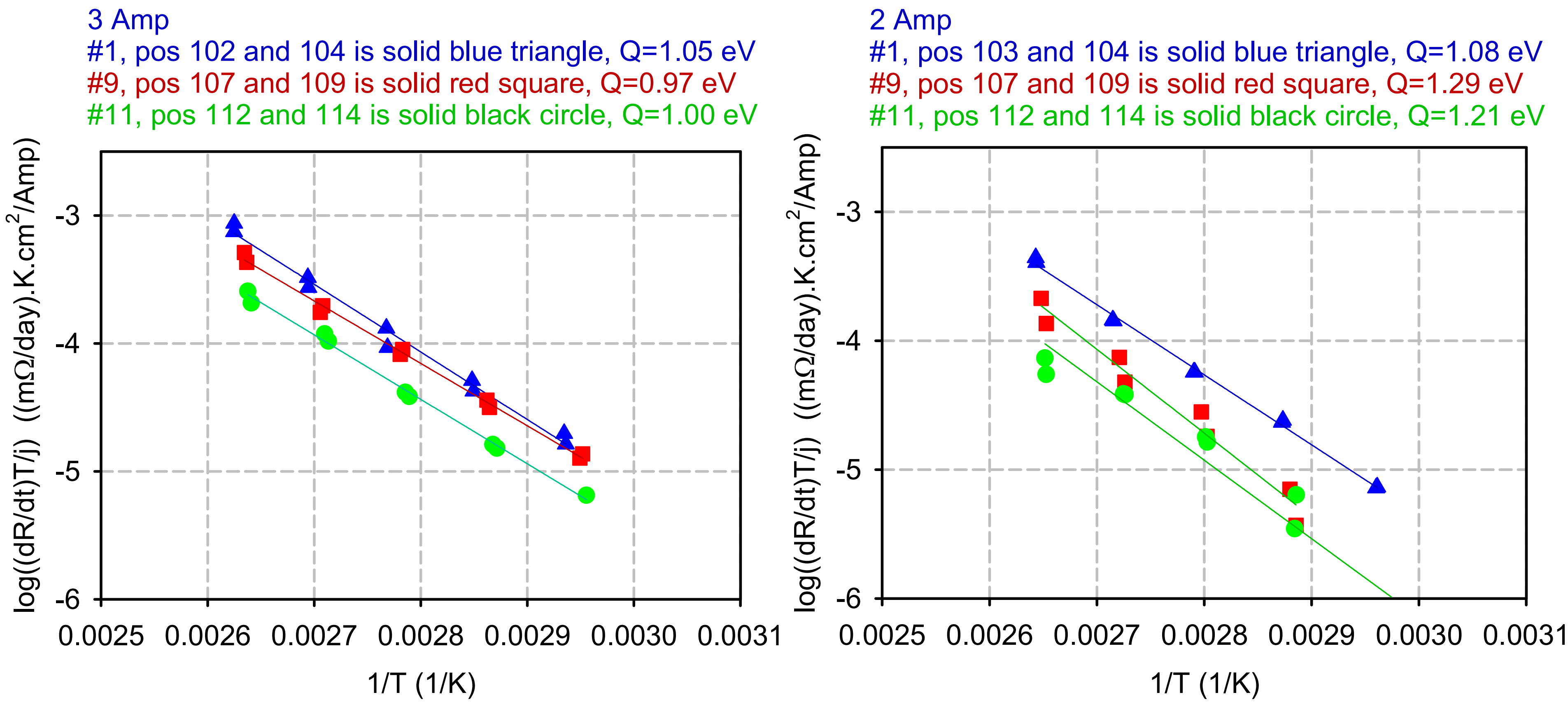




Run 4: #1=58Bi; #9=40Bi-0.5Cu-0.05Ni; #11=40Bi-1Ag-0.5Sb-0.5Cu-0.3Ni

Sb addition decreases EM.

Hypoeutectic Sn-Bi alloys have lower EM.

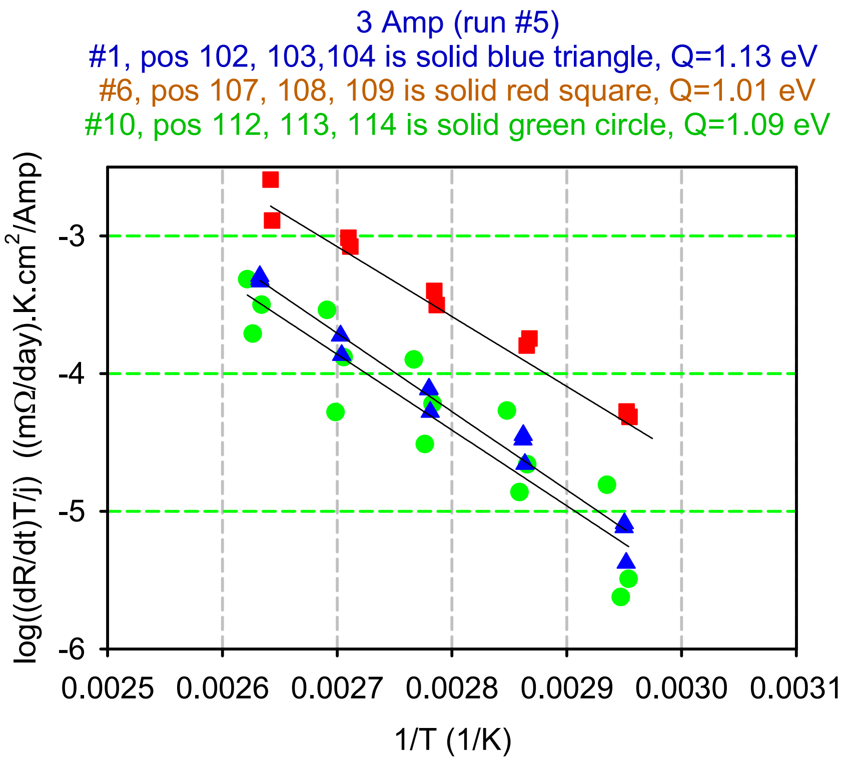


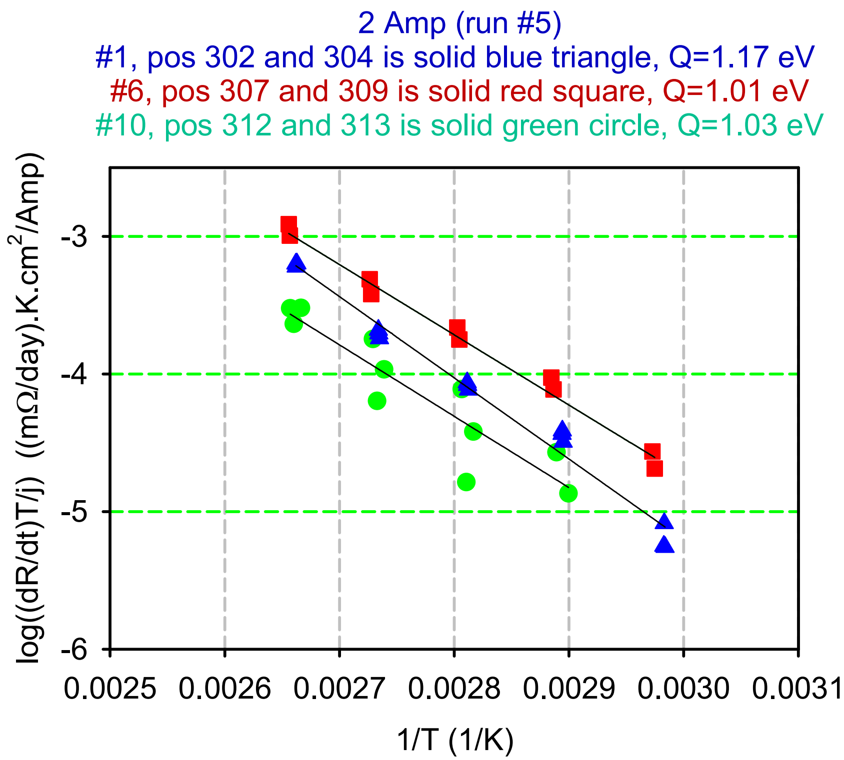
Run 5: #1=58Bi; #6=57Bi-1.2Ag-0.2Cu; #10=37Bi-<1Ag-<1Sb

Sb addition decreases EM.

Ag addition increases EM.

Hypoeutectic Sn-Bi has lower EM.

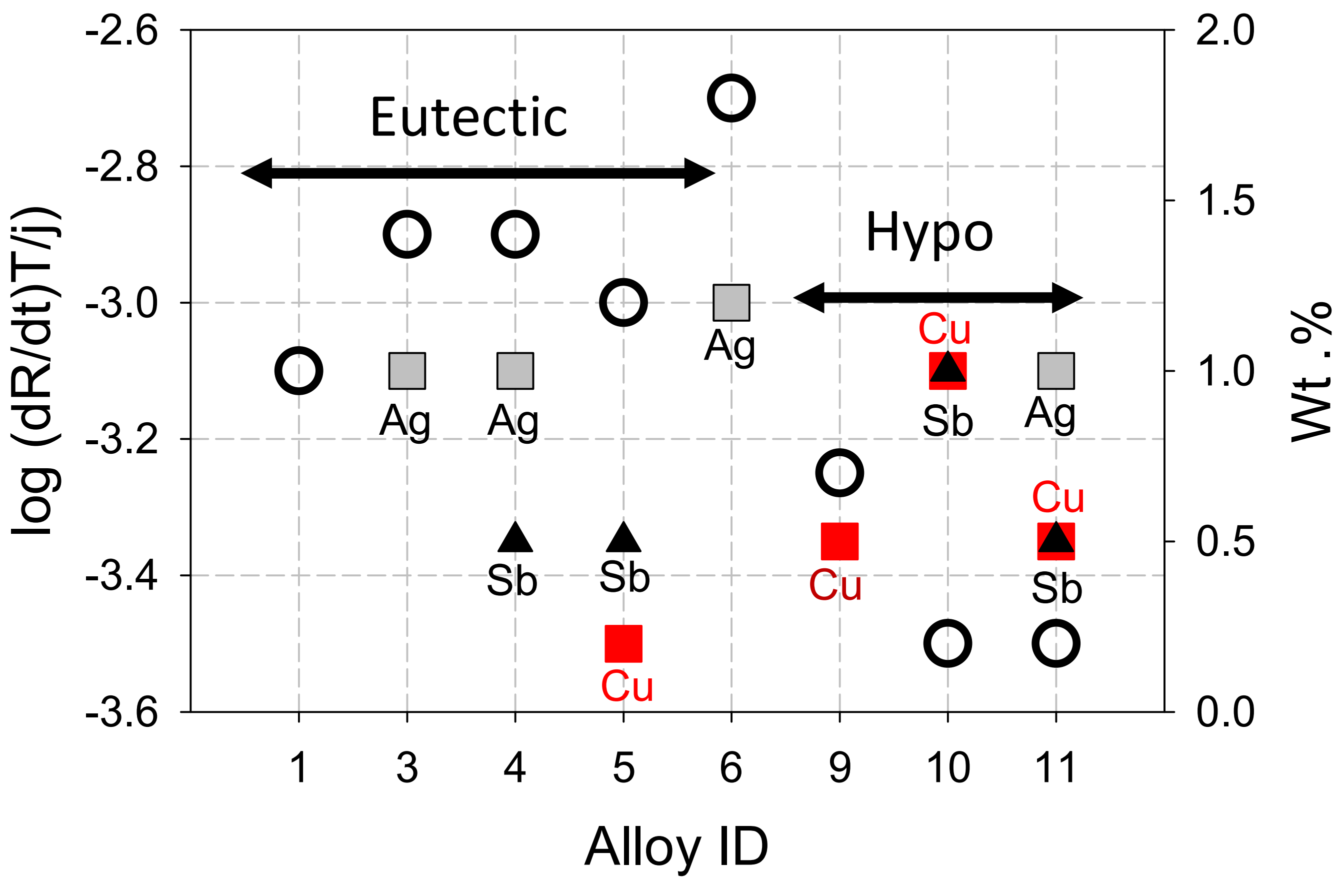




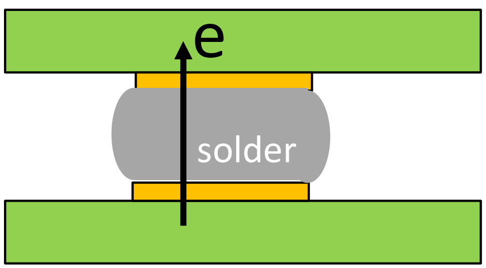
Hypoeutectic Sn-Bi alloys have lower EM rates.
Ag increases EM rates. Sb decreases EM rates.

Alloy ID	Run #	Alloying additions tin (wt. %)					**log((dR/dt)T/j) log((mW/day)K.cm^2/Amp) at 3 Amp**
		Bi	**Ag**	**Cu**	**Ni**	**Sb**	
#1	2, 3, 4, 5	58	--	--	--	--	**-3.0, -3.0, -3.1, -3.3**
#5	3	57	——	——	0.015	0.5	**-3.0**
#3	2	57	1	--	--	--	**-2.9**
#4	3	57	1	--	--	0.5	**-2.9**
#6	5	56	1,2	0.2	ppm	--	**-2.7**
#9	2, 4	40	--	0.5	0.03	--	**-3.3, -3.2**
#10	5	37		<1		<1	**-3.5**
#11	4	40	1	0.5	-0.3	0.5	**-3.5**

Ag additions increase EM rates. Cu+Sb decrease EM. Hypoeutectic Sn-Bi alloys have lower electromigration rates.



Electromigration in SAC305 solder using the bottom-terminated component (BTC) approach



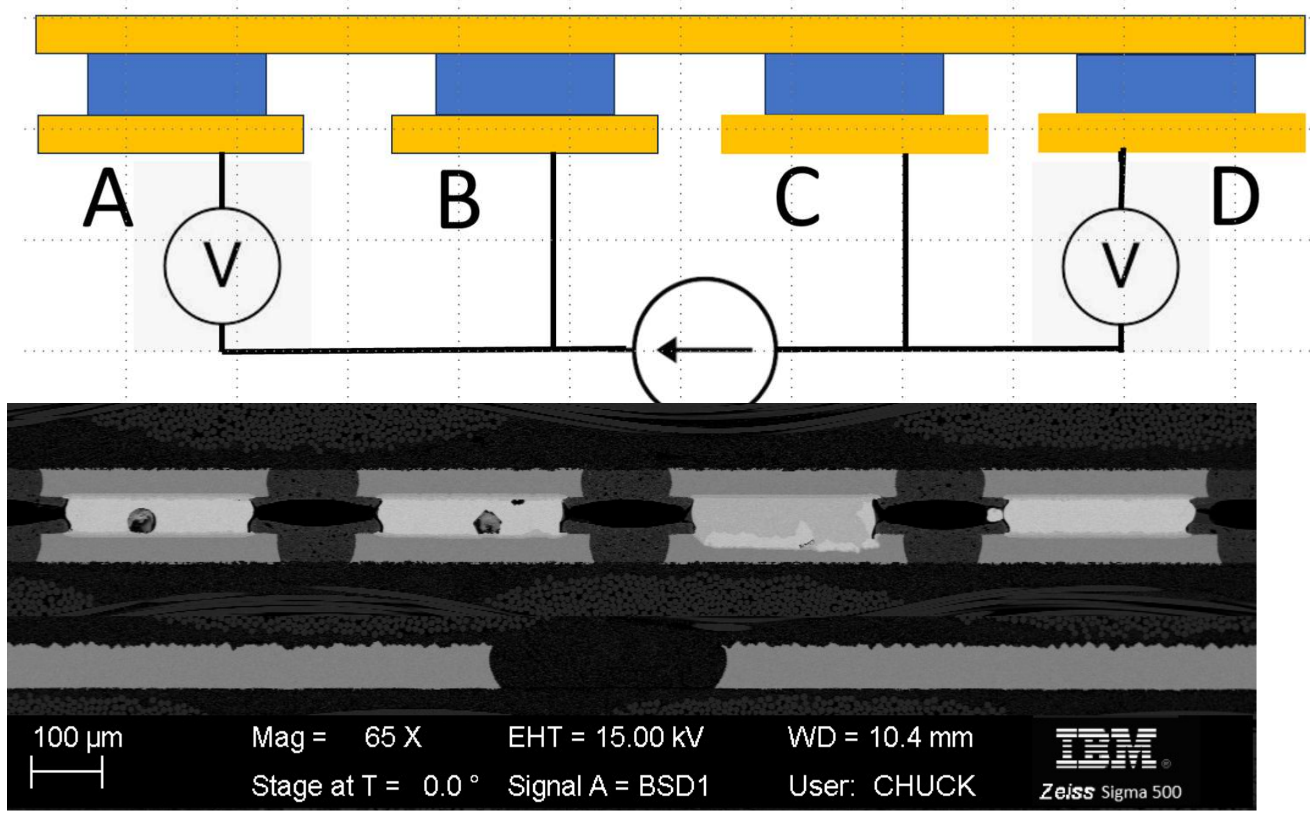
SAC305 is a tin-based solder containing 3 wt. % Ag and 0.5 wt. % Cu

Test card with bottom-terminated component (BTC) solder joints

Area = 0.25x0.60 mm^2

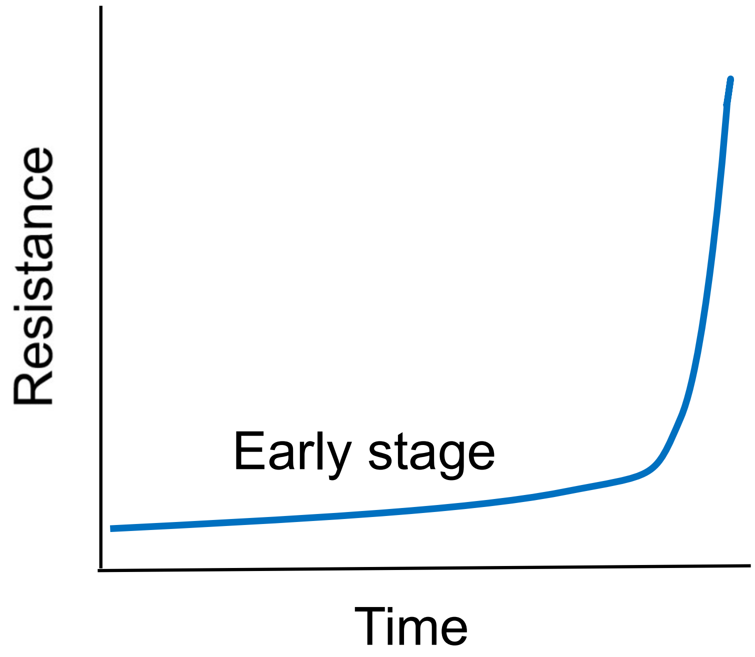
j = 2.7 to 5.3 kA/cm^2

Temp = 93 to144 ^oC



SAC305 (3 wt. Ag, 0.5 wt. % Cu)

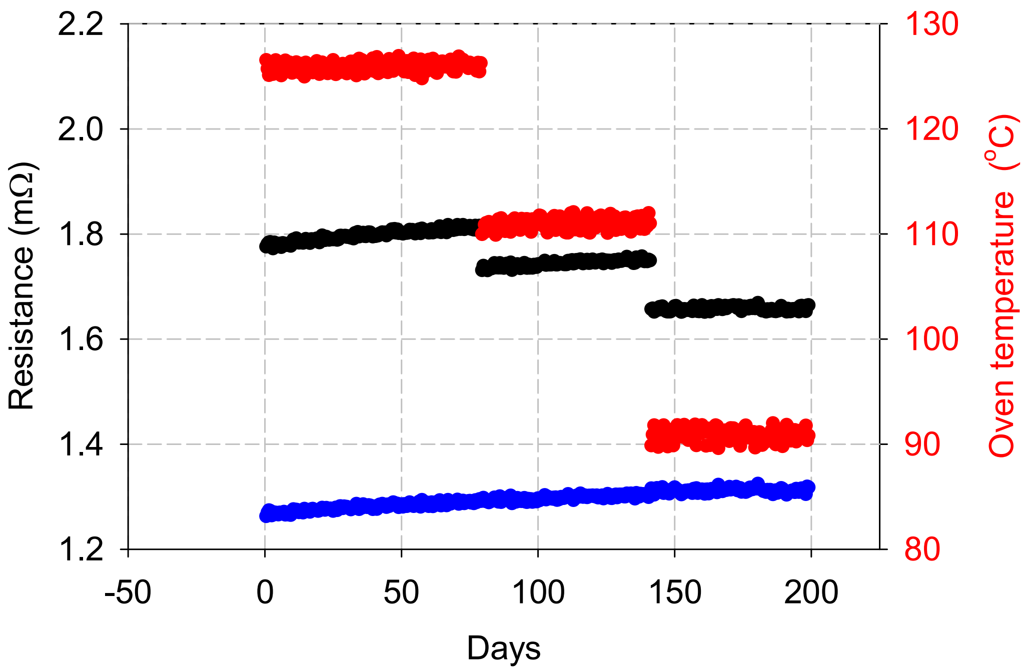
Explaining the physics of the early stage of electromigration before the voids, growing at the cathode, coalesce into an open circuit.



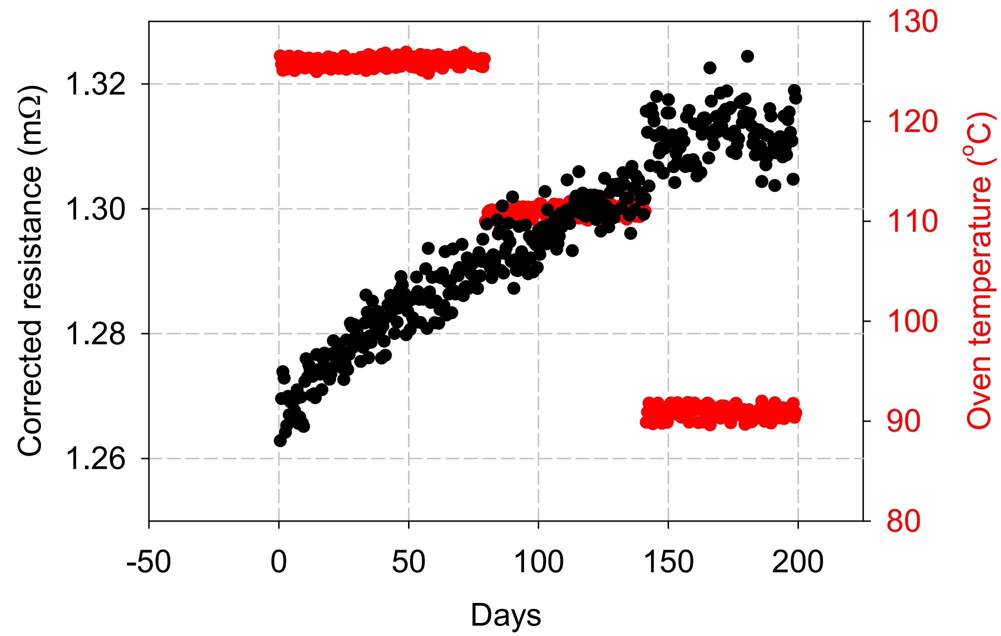
Resistance normalized to room temperature

101 OSP-OSP
α = 0.004 /°C
Black plot is for measured resistance temperature
The blue plot is for resistance normalized to 25 °C

$$R_{25} = \frac{R_1}{1+\alpha\left(T_1 - 25\right)}$$



101 OSP-OSP
α = 0.004 /°C



SAC305 electromigration rates

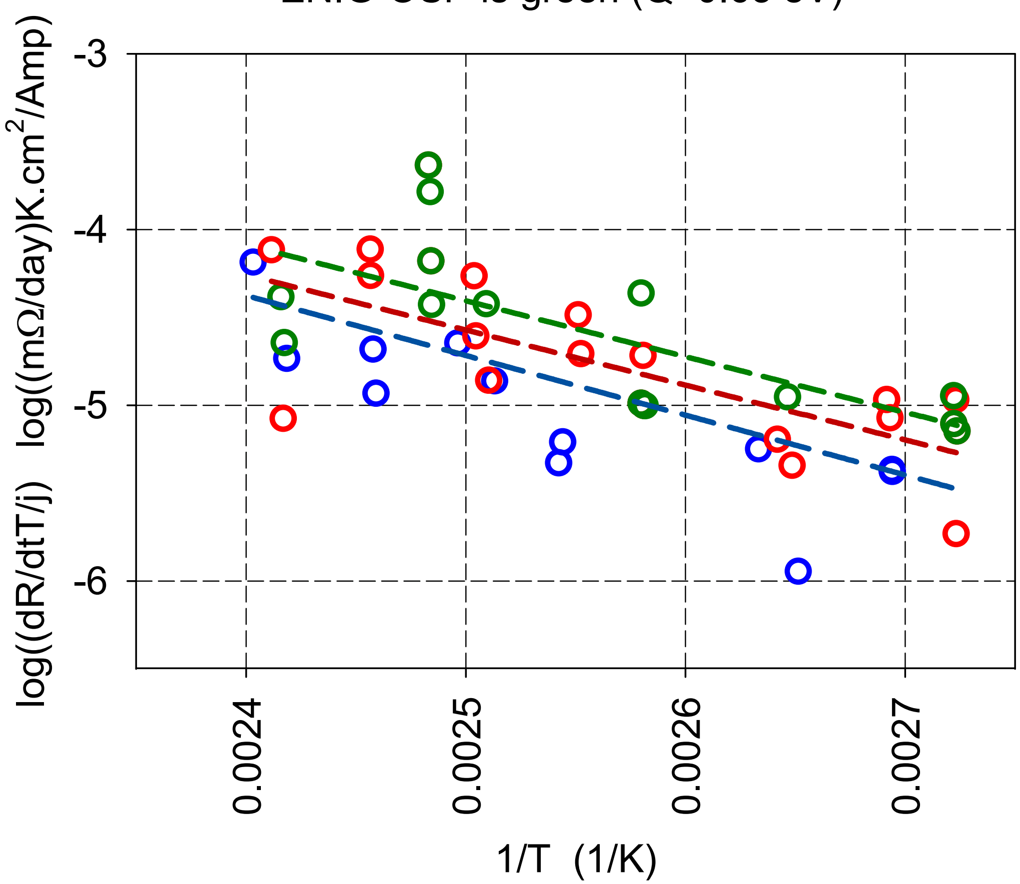
$$v = \frac{DF}{kT} = \frac{DZ^{*}e\mathrm{E}}{kT} = \frac{DZ^{*}e\rho j}{kT}$$

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

$$v \propto \frac{\Delta R}{\Delta t} = \frac{\Delta R}{days}$$

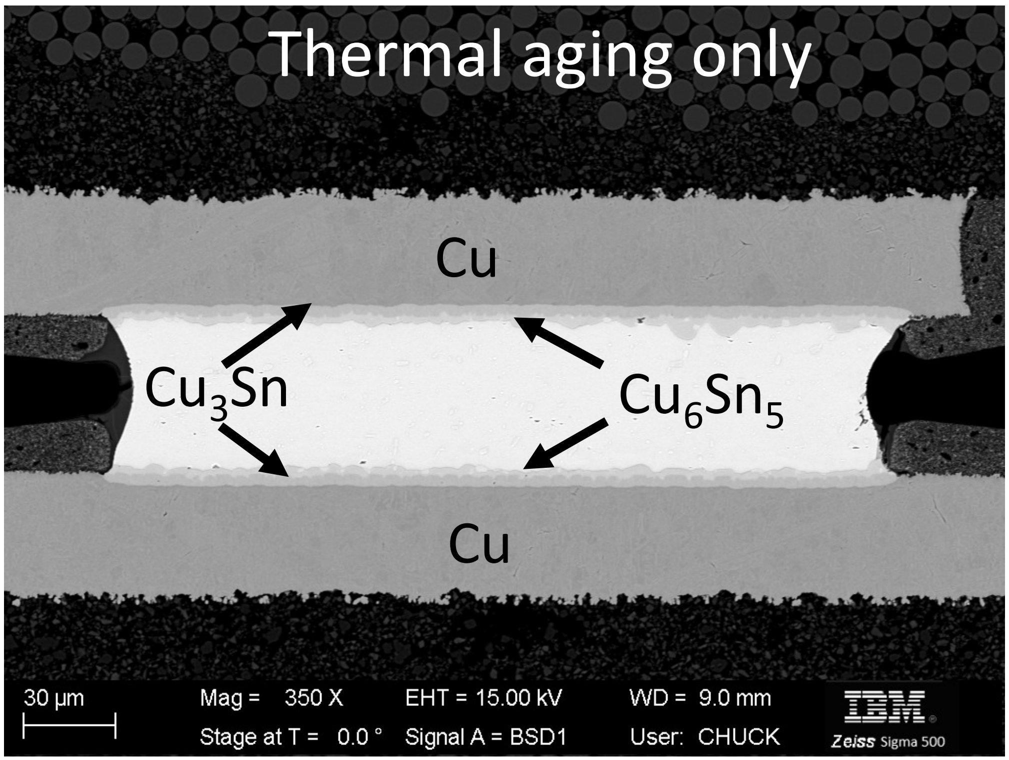
$$\frac{\left(\Delta R/days\right)T}{j} \propto \frac{D_0 Z^{*}e\rho}{k} e^{-\frac{Q}{kT}}$$

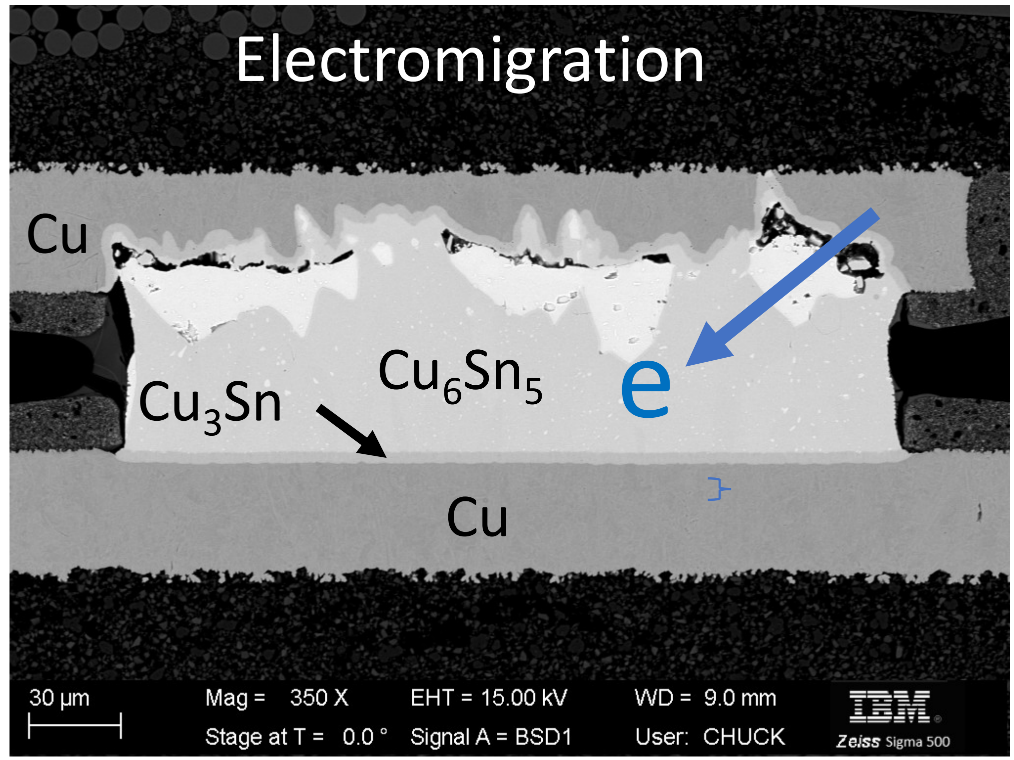
SAC BTC
OSP-OSP is blue (Q=0.68 eV)
ENIG-ENIG is red (Q=0.62 eV)
ENIG-OSP is green (Q=0.63 eV)



Electromigration in OSP-OSP SAC solder joint at 4 Amp

80 days at 126 °C, 60 days at 111 °C and 60 days at 91 °C

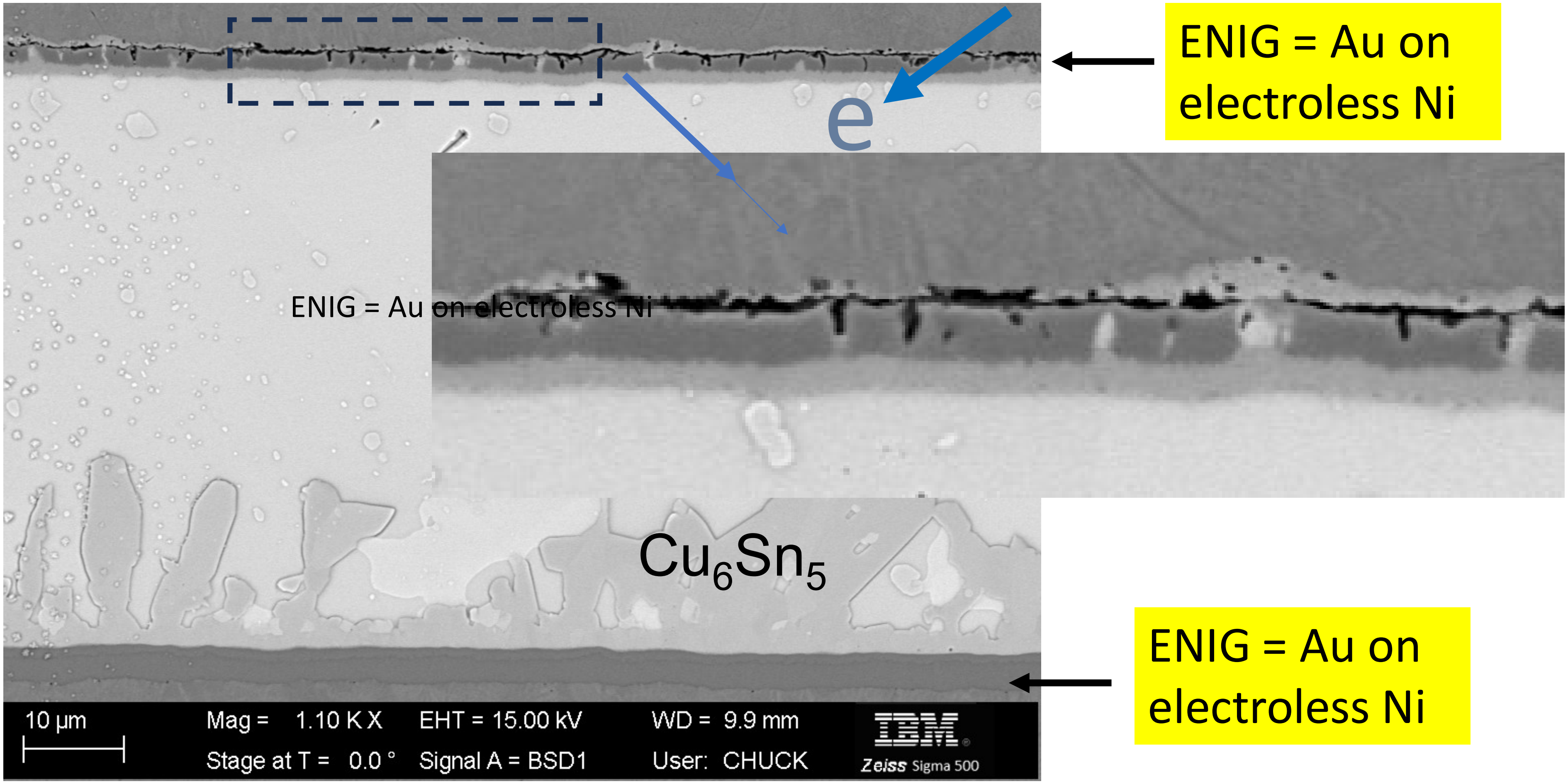




The Cu_6Sn_5 grew from the anode towards the cathode.

Electromigration in ENIG-ENIG SAC solder joints

80 days at 126 °C, 60 days at 111 °C and 60 days at 91 °C

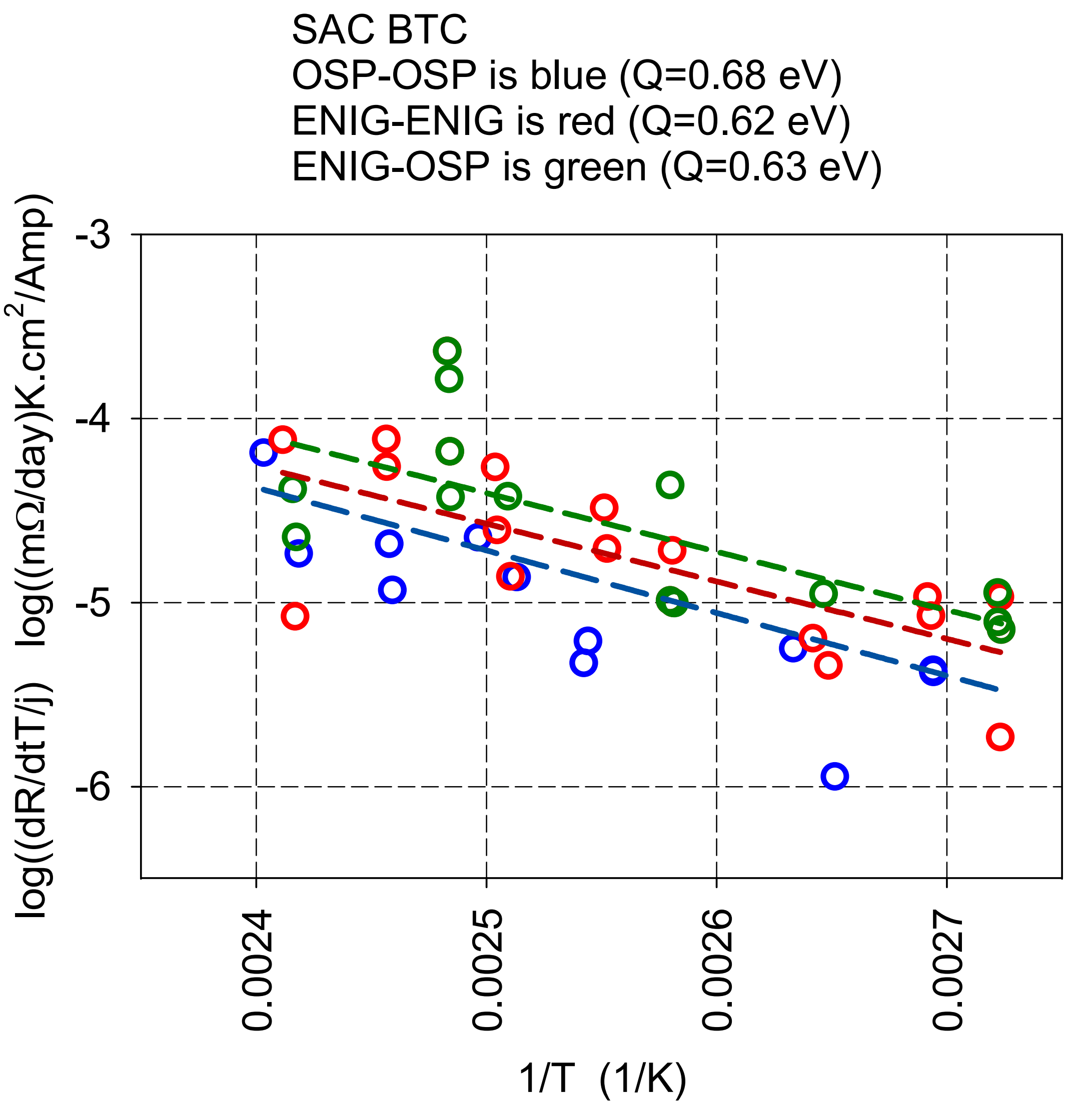


The SAC305 solder electromigration activation energy is 0.62-0.68 eV.

The Sn-Cu intermetallic growth activation energy is 0.61-0.93 eV.

The Cu electromigration activation energy is 0.34 eV.

Based on activation energy, the SAC305 resistance increase is due to the Cu_6Sn_5 intermetallic growth.



Prabjit (PJ) Singh

singh.prabjit@gmail.com

+1-845-489-4349