Evaluation of electromigration in flip-chip solder joints

Hyun-Kyu Lee, Yong-Chul Chu, Myung-Ho Chun, Sang-Ho Jeon
Jung-Ug Kwak, Seung-Jin Lee, Sung-Mun Bae
R&D center, DUKSAN HI-METAL CO., LTD
597-3, Yeonam-Dong, Buk-gu
Ulsan, Korea, 683-804
Phone : 82.52.283.9042, Fax : 82.52.289.3500, hyun3005@dshm.co.kr

Abstract

The flip-chip solder joint has become one of the most important technologies of high-density packaging in the microelectronics industry. But, electromigration has become a critical reliability issue in flip-chip technology. Because the dimensions of solder joints are expected to decrease and current density is expected to increase.
This study is about electromigration of flip-chip solder joints, we evaluated many kinds of solder balls such as SnAgCu, SnCu and so on in flip chip package. The lifetime against electromigration was defined the fail from the value of resistance with electric current reaches 1.5 times of that of initial resistance with electric current for.
In solder bumps with electric current, since the atoms composed of the solder bump and UBM move in the direction of electron flows, the IMC was accumulated on the anode side. Meanwhile, the IMC disappeared in the cathode side, and the voids were formed. In the solder bumps without electric current, the IMC gradually grew on both sides.
SnAgCu had better lifetime than SnCu, and different time-to-failure caused by different crystallographic orientation of Sn. And various dopants in SnCu had a different EM lifetime each other.

Key words : flip chip, electromigration, electric current, crystallographic, EBSD

1. Introduction

Electromigration is the transport of material caused by the gradual movement of the ions in a conductor due to the momentum transfer between conducting electrons and diffusing metal atoms. According to recent report from Tu, [1] when current density of flip-chip package reaches more than 10^4A/cm^2, the metal atoms of UBM (under bump metallization) into the solder at the cathode, observation for significant movement of metal atoms such as IMC growth at the anode. As a result of these things, the micro voids were formed at the cathode and hillock also was formed at the anode. It is caused poor realiability for a solder joints by micro voids and hillock. The Flip-chip solder joint at the cathode, we found a fast, an asymmetrical, a localized dissolution of Cu.[2] Under a current density of 10^2 ~ 10^3 A/cm^2, IMC thickness from Sn/Ni, Sn/Ag, Sn/Cu solder joint has influenced the current direction.[3] Although this current density level is still about two orders of magnitude lower than that for Cu interconnects, EM damages becomes a serious concern for solder joints dou to their low current carrying capability.[4] In solder joints, the formation of intermetallic compounds (IMCs) at the interface between the solder and the UBM plays an important role in controlling EM reliability.[5] Noble or near noble metals such as Cu or Ni in the UBM can diffuse rapidly in Sn by an interstitial diffusion mechanism,[5~7] and react at a fast rate with Sn to form IMCs.[8]

The implementation of eco-friendly Pb-free solders generates further interests in studying the effect of UBM on EM reliability of solder joints. This effect is expected to be more significant for Sn-based Pb-free solders. Since Sn is a major constituent of the IMCs, its inexhaustible supply from the solder can greatly enhance the IMC formation to degrade EM reliability.[2,8]

In this work, the electromigration behavior between UBM and Solder ball was studied. The evolution of the surface microstructure of the electromigration couple specimen was monitored by in situ observation under current stressing, and the undersurface microstructure of the specimen was observed using a scanning electron microscope (SEM) after the electromigration test to investigate the microstructure variation in greater detail. The effect of chemical portential and electromigration on the formation of IMCs and the diffusion behavior of UBM were also investigated.

2. Experimental procedure

In this study, we have used Sn-3.0Ag-0.5Cu, Sm-0.7Cu, Sn-0.7Cu-0.08Ni ball and ball size was 200um. This is a schematic of the flip-chip pkg. with Sn-3.0Ag-0.5Cu solder as shown Fig.1.

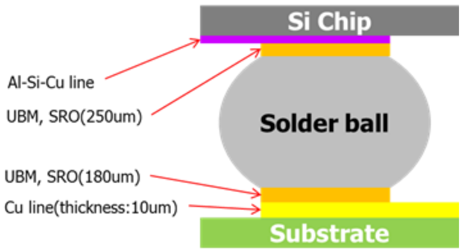
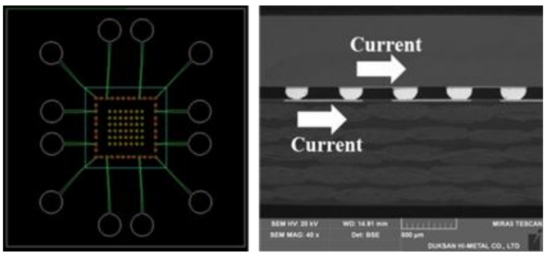


Fig. 1. Schematic of the test bump

We used the wafer which has a Cu plating based on seed metal for the electromigration. The thickness of Cu plating is 8um and width is 300um. And then Wafer (Cu plating) was plated Ni and Au again. Ni thickness is 5um and Au thickness is 0.5um. The whole of wafer thickness is 600um. The substrate was plated 5um Ni(P) on the Cu metallization and 0.03um Au on the Ni layer for preventing the oxidation. Fig.2 schematic shows the daisy chain to connect the electrical after solder ball assembly.

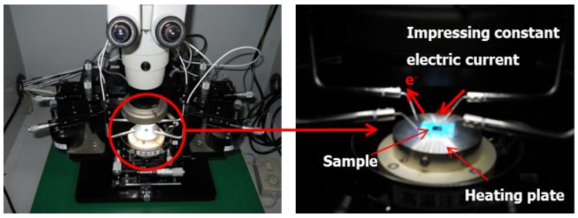


(a) (b)

Fig. 2. (a) Package design and (b) SEM image of the electromigration test configuration

The reflow condition was peak temp. 240℃, 40sec (over 220℃) for soldering with solder balls and pkg. and the flux cleaning condition was 60℃ for 10 minutes using only distilled water. At this time, we used WS type flux for this study. After completing electromigration, we have observed solder deformation shape on the specimen made by using only epoxy resin. We used the Tin etching water to know about IMC change or movement and UBM diffusion. The Tin etching water is 95 vol% C_2H_5OH, 4 vol% HNO_3,1 vol% HCL.

Fig.3. is shown the test machine for this study. Electromigration equipment can be divided into the current portion, a temperature portion and resistance portion. The resistance change by joule heating increase in proportion to resistance. Therefore, the amount of current applied to the specimen caused by the increase in the temperature of the specimen can be predicted. According to the JEDEC standards,[9] EM failure on the Flip-chip joint is defined as the electrical resistance is over 20% compared to the initial resistance. However, in this study, the lifetime of the specimen was measured the beginning resistance first, and then we set when it was 1.5 times compared to the beginning resistance. And this is a real time measurement. At this time, the specimen was applied to temperature 150℃ and current 1.0A.



(a) (b)

Fig. 3. Electromigration test machine (a) MX-400 model and (b) Magnification on test area

3. Results and discussion

We have studied the electromigration by using Sn 3.0wt%Ag0.5wt%Cu solder and Flip-Chip pkg. Fig.4. shows x-section image to find the electromigration behavior specimen used was. Direction of electron movement is shown by an arrow. If the current density was relatively low, the void was shown boundary surface between the solder and the IMC layer by migration at the cathode side. We found that the IMC formation in the solder and the solder with the IMC of the electrode interfacial at the anode side were grown. However, in case of high current density, migration of electrode materials lead to loss of cathode side electrode.[10~14] In this study, moving in the direction of movement of the electrodes was observed by loss of electrons due to a high current density. The causes and characteristics of EM phenomena in solder joints were movement of atom. The following is among their a mathematical formula.[15~18]

$$J_{EM} = C\frac{D}{kT}Z^{*}eE = C\frac{D}{kT}Z^{*}e\rho j \qquad (1)$$

Z*=effective charge number, e=electron charge, E=electric field, ρ=resistivity, j=current density, C=concentration of diffusion atom,

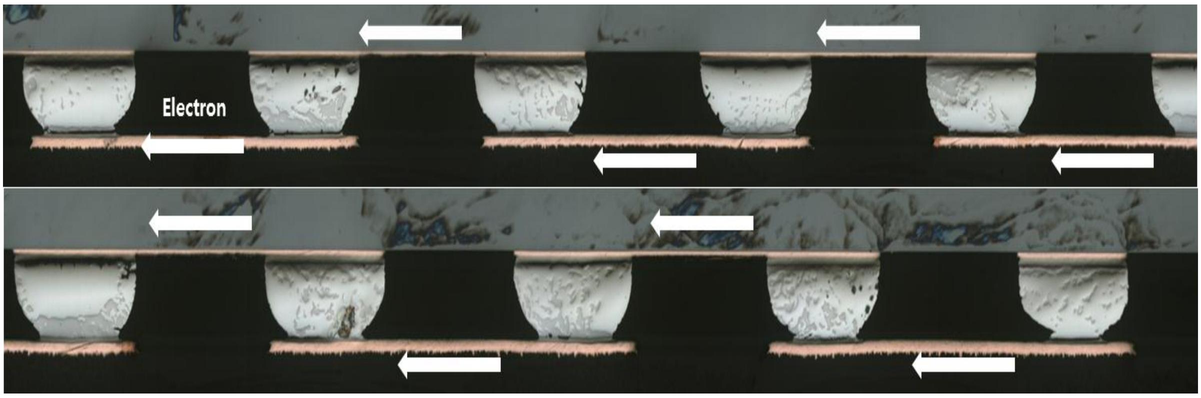


Fig 4. X-section image after finishing the electromigration test

D=thermally activated diffusivity, k=Boltzmann constant, T=absolute temperature. According to the mathematical formula, diffusion speed and current density had a decisive effect to atom movement.

In case of the solder ball size 100um for Flip-Chip, the current density for the solder joints was from $2x10^3A/cm^2$ to $5x10^4A/cm^2$. Each bump's current showed from 0.2A to 0.4A. It is a similar threshold current density ($1x10^4A/cm^2$) of Sn,[17] so migration can be happened easily. Also, inside temperature of the chip rises above 100℃ due to the effect of joule heating, the effect of current crowding by structural problems at the flip-chip solder joints, current density can be more than 10 times higher locally in the area.[19] So, an aging of EM at the flip-chip solder joint can accelerate by those things. Firstly, we must know about the Sn aeolotropies to explain the EM at the flip-chip solder joint. Sn belongs to tetragonal crystal structure at room temperature and a-axis & b-axis is 0.583nm, c-axis is 0.318nm with big aeolotropies. According to current report, [001] direction the modulus of elasticity and young's modulus has a bigger than [100] direction. Coefficient of expansion is greater 2 times and the structure of solder can be change the characteristic of Sn.[20~24] C-axis direction can lead to spread of interstitial space is greater than a-axis and b-axis,[25] atoms of Au, Ni, Cu within the diffusion rate, depending on the direction of each axis, there are big difference for diffusion rate. Especially, In case of Cu for using UBM(Under Bump Metallization) layer, c-axis direction diffusion speed was faster than a-axis and b-axis about 500 times at the room temperature [26~29] diffusion speed by Sn direction impurity atoms as shown the table1. According to Lu,[30] he found the change of aging speed by EM in same sample and if between electron flow and Sn c-axis is parallel, UBM can be faster dissolution than C-axis and if c-axis was verticality, Sn's EM can be happened. However, there is no enough report that explanation aging mechanism by Sn crystal grain direction at flip-chip solders joints and method for preventing of high-speed aging.

Table 1. Diffusion codfficient of various atom in the Sn matrix respect to axis direction.[26~29]

Atom	Direction	Diffusion coefficient (㎠/sec) at 25℃
Cu	$D_{Cu\ in\ Sn\ a(\perp)}$	$3.8x10^{-9}$
	$D_{Cu\ in\ Sn\ c(\parallel)}$	$1.0x10^{-6}$
Ni	$D_{Ni\ in\ Sn\ a(\perp)}$	$6.0x10^{-12}$
	$D_{Ni\ in\ Sn\ c(\parallel)}$	$1.3x10^{-5}$
Au	$D_{Au\ in\ Sn\ a(\perp)}$	$1.6x10^{-14}$
	$D_{Au\ in\ Sn\ c(\parallel)}$	$4.9x10^{-11}$
Ag	$D_{Ag\ in\ Sn\ a(\perp)}$	$5.7x10^{-15}$
	$D_{Ag\ in\ Sn\ c(\parallel)}$	$6.8x10^{-12}$
Sn	$D_{Sn\ in\ Sn\ a(\perp)}$	$2.1x10^{-18}$
	$D_{Sn\ in\ Sn\ c(\parallel)}$	$1.0x10^{-18}$

The cross-sectional images of the assembled Sn3.0Ag0.5Cu for electromigration test at 150℃ in fig.5. At this time, current density received from the Si-chip and substrate is $2.3x10^3$ A/㎠, $4.0x10^3$ A/㎠. At this time, Current density obtained by calculating UBM opening. The direction of movement of electrons displayed "e", in case of the left side bump, the direction of the electrons to move from bottom to top and in case of right side bump, the direction of the electrons to move from top to bottom. We found the electromigration destruction at the cathode side of bump in our tested specimen. Between UBM and solder, it made the IMC's (Cu_6Sn_5, Cu_3Sn) at the cathode. Also, the intermetallic compound was lost depending on the movement of electrons and made the voids. The form of movement along UBM for electron is similar Blech specimen[31] used Al electromigration study by Yeh. According to the Yeh report, he found Al loss at the cathode, but Al stick at the anode.[31] However, UBM was consumed also in this study, we could not find the hillock at the anode side.

Fig.6 shows the impressed voltage change form test time on Sn 3.0Ag 0.5Cu, Sn 0.7Cu, Sn 0.7Cu 0.08Ni solder at 150℃ room temperature

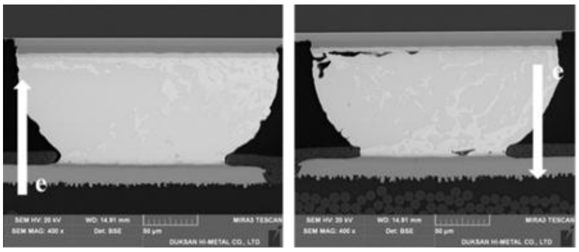


Fig. 5. SEM micrographs of the Sn 3.0Ag 0.5Cu solder bumps observed after electromigration failure

from the beginning of the test to last moment of failure, flip-chip's impressed voltage was not change, however when failure moment, the impressed voltage was increased. As a result of Solder bump microstructure on eatch step of electromigration by Choi report, it found the voids the solder bump of the cathode side with no signal of resistance change at the last moment of failure.[32] The electronic failure by solder bump electromigration was crop up. So the electromigration of solder bump can be serious repercussions for reliability of flip-chip. Fig.6. and table.2 shows electromigration MTTF about voltage changing test.

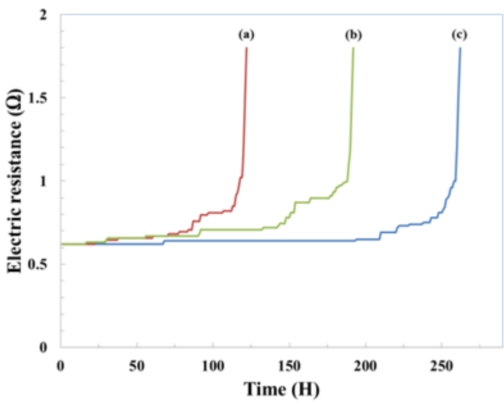


Fig. 6. Electric resistance(Ω) vs time(H) curve obtained during electromigration test at 150℃ (a) Sn 0.7Cu (b) Sn 0.7Cu 0.08Ni (c) Sn 30.Ag 0.5Cu

We used "Black equation" for Electromigration's MTTF as shown a mathematical formula 2.[33] T : Temp. j : Current density, A and n is constant, Q is a activation energy for electromigration, and k is Boltzmann's constant.

$$\text{MTTF} = A \cdot j^{-n} \cdot \exp\left(\frac{Q}{kT}\right) \qquad (2)$$

Sn3.0Ag0.5Cu solder has a better than Sn0.7Cu and Sn0.7Cu 0.08Ni for electromigration life time. Sn3.0Ag0.5Cu's life time is longer than others.

Table 2. Mean-time-to-failure (MTTF) for electromigration of the Sn 3.0Ag 0.5/cu, Sn 0.7Cu, Sn 0.7Cu 0.08Ni solder bump.

	Sn 0.7Cu	Sn 0.7Cu 0.08Ni	Sn 3.0Ag 0.5Cu
MTTF	118 hr.	189 hrs.	258 hrs.

The change of Solder ball in EM has influenced reorientation and rotation of Sn crystal grain and Cu atom is speed up for migration.[34~35]

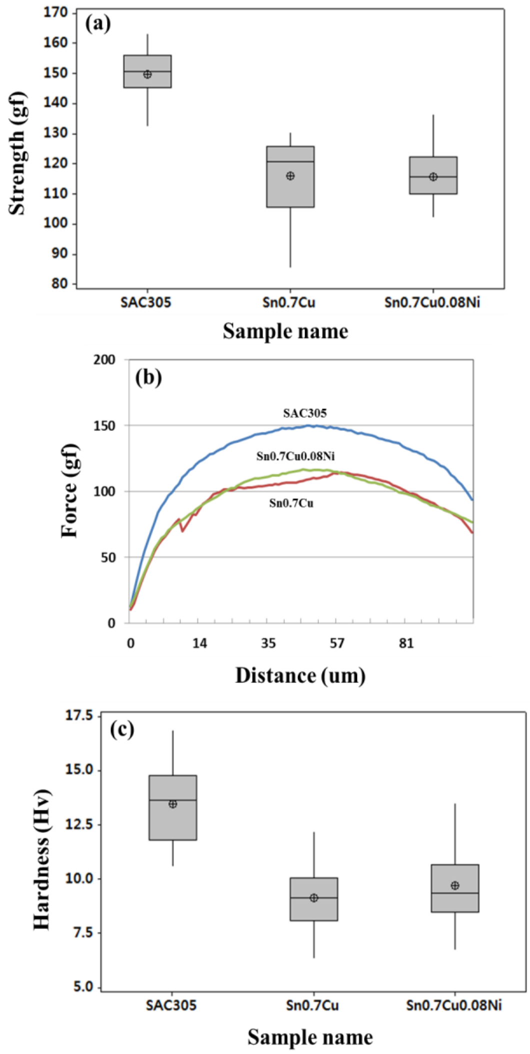


Fig. 7. Fig. 4. Mechanical strength of the joint with various solders. (a) Ball shear strength (b) Interrelation between force and displacement (c) Hardness

The reason of SnAgCu solder has a longer life time than SnCu solder is Ag. We have studied the electromigration for Ag. SnAgCu solder has the IMC such as Ag_3Sn after reflow.[36] Ag didn't have a influenced the electromigration. Also, Ag is due to have to effectively suppress the proliferation of Cu-Sn intermetallic compound. The electromigration lite time depends on the IMC's melting point and diffusion coefficient.

Ni's diffusion coefficient is slower than Cu's diffusion coefficient in Sn at 150℃.[26~29] Also, Ni_3Sn(high melting point) IMC have a bigger binding energy than Cu_6Sn_5 (low melting point). Therefore, Sn0.7Cu with 0.08Ni has a longer life time than Sn0.7Cu solder. There are needs of study for relationship with IMC growth, failure, deformation, Sn crystal orientation and electron flow to reveal the more sure mechanism.

Fig.7. shows BST strength of assembled Sn3.0Ag0.5Cu and Sn0.7Cu and Sn0.7Cu 0.08Ni solder with graph for the relationship between load and displacement, hardness. BST condition was 200um/s of test speed and height was 5um. Hardness was 100gf with 10sec. Ag contents solder had a higher hardness strength than no Ag contents solder. The fine grain and bulky IMC in the solder made interruption for a crack path. Sn0.7Cu and Sn0.7Cu 0.08Ni, it showed similar hardness, as we can know from graph of load and displacement, there were similar deformation. We found from this study, Sn0.7Cu which has a large ductile solder was better than others for using flip-chip pkg. to minimize for warpage crack by insulation layer.

However, Sn0.7Cu solder has a weakness for electromigration. But if Ni is dopanted into the Sn0.7Cu, the performance of electromigration can be improved.

4. Conclusion

We found the electromigration behavior of Flip-Chip bump by using Sn 3.0Ag 0.5Cu, Sn 0.7Cu, Sn 0.7Cu 0.08Ni solder

(1) The IMC moved by the electromigration of Sn3.0Ag0.5Cu solder bump from cathode to anode and we found the void and failed circuit at the cathode.

(2) The average life time of Sn 3.0Ag 0.5Cu, Sn 0.7Cu, Sn 0.7Cu 0.08Ni solder bump was measured each time. The life time was 258, 118 and 189 hrs. each other. The reason of the longest in Sn3.0Ag0.5Cu solder bump was Ag_3Sn IMC which did not contribute to the electromigration. Also, Ag_3Sn was shown to effectively suppress the Cu-Sn intermetallic compounds due to suppress atom movement.

(3) The result of BST & hardness, SnAgCu alloy was higher than Sn0.7Cu and Sn0.7Cu0.08Ni. Sn0.7Cu and Sn0.7Cu0.08Ni, there were no big differences.

(4) It is suitable to use of soft solder such as Sn0.7Cu to minimize the warpage crack on Flip-Chip pkg. which has a low permittivity. But it has a weakness of electromigration. However, we found the dopant such as Ni for protecting a weakness of electromigration.

Reference

[1] K.N. Tu, C.C. Yeh, C.Y. Liu and C. Chen, Appl. Phys. Lett. 76 (2000), p. 988.

[2] Y.C. Hu, Y.H. Lin and C.R. Kao, J. Mater. Res. 18 (2003), pp. 2544.

[3] S.W. Chen and C.M. Chen, J. Min. Met. Mater. Soc. 55 (2003), pp. 62.

[4] K.N. Tu, J. Appl. Phys. 94, 5451 (2003)

[5] B.F. Dyson, T. Anthony, D. Turn bull, J. Appl. Phys. 37, 2370 (1966)

[6] W.K. Warburton, D. Turnbull, in diffusion in solids, des. By A.S. Nowick, J.J. Burton (Academic, New York, 1975), pp. 171~226

[7] D.L. Decker, C.T. Candland, H.B. Vanfleet, Phys. Rev. B 11, 4885 (1975)

[8] M. Ding, G. Wang, B. Chao, P.S. Ho. In Proceeding of IEEE 43rd Annual International Reliability Physics Symposium (San Jose, CA, April 2005), p.518

[9] JEDEC standard JEP 154, "Guideline for characterizing solder bump electromigration under constant current ans temperature stress", (2008)

[10] T.Lee, K. Tu, D. Frear, "Electromigration of eutectic SnPb and SnAg3.8Cu0.7 flip chip solder bumps and under-bump metallization", J. Appl. Hys., 90(9), 4502 (2001)

[11] J. Nah, F. Ren, K. Tu, S. Venk, G. Camara, "Electromigration in Pb-free flip chip solder joints on flexible substrates", J. Appl. Phys., 99(2), 023520 (2006)

[12] M. Jen, L. Liu, Y. Lai, "Electromigration on void formation of Sn3.5Ag1.5Cu FCBGA solder joints", Microelectron. Reliab., 49(7), 734 (2009)

[13] T. Chiu, K. Lin, "The difference in the types of intermetallic compound formed between the cathode and anode of an Sn-Ag-Cu solder joint under current stressing", Intermetallics, 17(12), 1105 (2009)

[14] J.K. Choi, S.W. Jun, H.J. Won, B.Y. Jung, T.S. Oh, "Electromigration behavior of the flip-chip bonded Sn-3.5Ag-0.5Cu solder bumps", J. Microelectron. Package. Soc., 11(4), 43 (2004)

[15] Y. Chan, D. Yang, "Failure mechanisms of solder interconnects under current stressing in advanced electronic packages", Progress in Materials Science, 55(5), 428 (2010)

[16] C. Chen, S. Liang, "Electromigration issues in lead-free solder joints", L. Mater. Sci.: Mater. Electron., 18(1), 259 (2007)

[17] K. Tu, "Recent advances on electromigration in very large scale intergration of interconnects", J. Appl. Phys., 94(9), 5451 (2003)

[18] K. Tu, A. Gusak, M. Li, "Physics and materials challenges for lead free solders", J. Appl. Phys., 93(3), 1335 (2003)

[19] E.C.C. Yeh, W.J. Choi, K.N. Tu, P. Elenius, H. Balkman, "Current crowding induced electromigration failure in flip chip solder joints", Appl. Phys. Lett., 80(4), 580 (2002)

[20] A. Telang, T. Bieler, "Characterization of microstructure and crystal orientation of the tin phase in single shear lao Sn 3.5Ag solder joint specimens", Scr. Mater., 52(10), 1027 (2005)

[21] J. Rayne, B. Chandrasekhar, "Elastic Constants of a Tin from 4.2°K to 300°K", Phys. Rev., 120(5), 1658 (1960)

[22] H. Huntington, "The elastic constants of crystals", Solid state physics, 7, 213 (1958)

[23] D. House, E. Vernon, "Determination of the elastic moduli of tin single crystals, and their variation with temperature", British Journal of Applied Physics, 11(6), 254 (1960)

[24] T. Bieler, H. Jiang, L. Lehman, T. Kirkpatrick, E. Cotts, B. Nandagopal, "Influence of Sn grain size and orientation in the thermomechanical response and reliability of Pb free solder joints", IEEE T. Compon. Pack. T., 31(2), 370 (2008)

[25] V. T. Deshpande, and D. B. Sirdeshmukh, "Thermal expansion of tetragonal tin", Acta Crystallohr., 14(4), 355 (1961)

[26] B.F. Dyson, "Diffusion of gold and silver in tin single crystals", J. Appl. Phys., 37(6), 2375 (1966)

[27] B.F. Dyson, T.R. Anthony, D. Turnbull, "Interstitial diffusion of copper in tin", J. Appl. Phys., 38(8), 3408 (1967)

[28] F. Huang, H. Huntington, "Diffusion of Sb, Cd, Sn and Zn in tin", phys. Rev. B, 9(4), 1479 (1974)

[29] D. Yeh, H. Huntington, "Extreme fast-diffusion system: Nickel in single crystal tin", Phys. Rev. Lett., 53(15), 1469 (1984)

[30] M. Lu, D. Shih, P. Lauro, C. Goldsmith, D. Henderson, "Effect of Sn grain orientation on electromigration degradation mechanism in high Sn based Pb free solders", Appl. Phys. Lett., 92(21), 211909 (2008)

[31] E. C. C. Yeh and K. N. Tu, "Effects of contact resistance and film thickness in current crowding and the critical product of electromigration in Blech structures", J. Appl. Phys., 89(6), p.3203 (2001)

[32] W. J. Choi, E. C. C. Yeh, and K. N. Tu, "Mean time to failure study of flip chip solder joints on Cu/Ni(V)/Al thin film under bump metallization", J. Appl. Phys., 94(9), p.5665 (2003)

[33] J. R.Black, "Electromigration a brief survey and some recent results", IEEE Trans. Electron Device, ED-16(4), 338 (1969)

[34] A.T. Wu, A.M. Gusak, K.N. Tu, C.R. Kao, "Electromigration induced grain rotation in anisotropic conducting beta tin", Appl. Phys. Lett., 86(24), 241902 (2005)

[35] A.T. Wu, Y.C. Hsieh, "Direct observation and kinetic analysis of grain rotation in anisotropic tin under elecromigration", Appl. Phys. Lett., 92(12), 121921 (2008)

[36] M. Li, K.Y. Lee, D. R. Olsen, W. T. Chen, B. T. C. Tan, and S. Mhaisalkar, "Microstructure, joint strength and failure mechanism of SnPb and Pb-free solders in BGA packages", TEEE transactions on electronics packaging, vol. 25, (2002) pp. 185-192