A Brief Review on Electromigration Behaviours of Solder Joints Under Electrothermal Load

Zoltán Tafferner, Attila Géczy
Department of Electronics Technology
Budapest University of Technology and Economics
Budapest, Hungary
tafferner.zoltan@edu.bme.hu

Abstract—Solder joints in electric devices have been reducing in size for decades. The drive to fit more functions into a single device or package continues to drive innovation in the field. Sur-face mounted chip-sized components like resistors are now widespread in size of 0402 and 0201 (1x0,5 mm and 0,6x0,3 mm) and less, while BGA solder joints are even smaller, with chiplet technology driving inter-chip solder bumps into ≤100 µm range. The reduction in solder joints size means that the current density in the solder joint and the thermal load on the joint could be significantly higher than in the case of larger components. The increased electrothermal load may increase the components' tendency to show electromigration or thermomigration phenomena. These can lead to Cu pad dissolution, recrystallization and intermetallic-compound (IMC) thickening, all of which could influence the mechanical properties of the solder joints. Literature have shown that electromigration can reduce the reliability of the solder joints, however, there is an increasing need to validate electromigration or thermomigration in a robust manner. This paper is a review of current literature on electromigration behaviours in small scale solder joints, dealing with topics such as the effect of using different solder materials or doped solders.

Keywords—electromigration, doping, thermomigration, review

I. INTRODUCTION

Electronic devices have been reducing in size for decades. The drive to fit more functions onto a simple PCB (Printed Circuit Board) creates the need for a continual downscaling of device sizes, leading to downscaling of solder interconnection sizes. Chip sized components, such as resistors and capacitors are widely used in the industry in sizes of 0402 (1×0,5 mm) and 0201 (0,6×0,3 mm), but smaller packages also exist. Other widely used packages, like SOT-23-6 transistors or BGA (Ball Grid Array) devices have solder interconnections of similar sizes. The rise of new packaging technologies, such as WLCSP (Wafer Level Chip Scale Package) drives the size reduction of solder interconnections even lower, into the <100 µm scale. This reduction, without a similar reduction in current load leads to increased current densities in the solder. The increased current density, along with the larger amount of current crowding exacerbates the already existing electromigration (EM) phenomena.

The project supported by the Doctoral Excellence Fellowship Programme (DCEP) is funded by the National Research Development and Innovation Fund of the Ministry of Culture and Innovation and the Budapest University of Technology and Economics.

Electromigration may cause the thickening of IMC (Intermetallic Compound) layers inside the solder joints [1], [2], [3], along with Cu dissolution at the cathode of the solder joint [4], [5], [6], and Kirkendall-void formation [6], [7], [8]. These effects may reduce the mechanical stability of the joint, which can be seen in shear strength for example [9]. The reduced shear strength and difference in CTE (Coefficient of Thermal Expansion) coupled with Joule-heat from the high current density may lead to crack formation inside the joint, and therefore a failure of the device. Other effects, such as dynamic recrystallization may also be triggered by the high electric currents [10], [11].

While electromigration has been investigated since the 1900s, with works such as [12], it is still not fully understood. The behaviour of different solder materials, such as SAC (Sn-Ag-Cu) [1], [13], Sn-Bi [14], [15] or Sn-Bi [16], [17] are still being investigated and compared [6], [15]. The effect of grain orientation and microstructure [18], [19], [20] of the solder joint on electromigration, the effect of solder geometry [21], [22] and volume [23] are also being investigated. The introduction of solder joints structures such as Cu-core solder joints [24] could also increase the risk of developing electromigration, as shown in [25]. There is also work relating electromigration in composite solder materials (alloyed solder or solder doped with nanoparticles), showing promising results [26], [27], [28]. This paper seeks to provide a review of literature, with a focus on publications after 2020.

II. Basics of Electromigration

A. *Definition of electromigration*

During the flow of electrons inside a conductor, the electrons will collide with the atoms of the conductor. As a result of the collision, momentum is transferred from the electron to the atom. This transfer of momentum creates a force acting upon the atom. This is called the electron wind force. The electron wind force F_e acts opposite to the electric field F_E. If the electron wind force is sufficiently high to overcome the electric field and the bonding forces of the conductor, the atom will be moved from its original position. The transportation of atoms because of the electron wind force is called electromigration. The forces acting on an atom are shown in Fig. 1.

The electron wind force can be expressed as (1):

$$F_e = Z^* e\rho j \quad (1)$$

Where Z^* is the effective charge number, e is the electron charge, ρ is the resistivity and j is the current density.

B. *Atomic fluxes during electromigration*

During electromigration, the force on the crystal atoms will create an atomic flux across the solder joint. Electromigration testing and field use of electric devices will often also include significant amounts of Joule-heat being generated, raising the temperature of the solder joint. The increased temperature, which can be in the range of ~150 °C, may be high enough that atomic flux due to chemical migration becomes relevant [6], and temperature gradient inside the joint may be enough to introduce thermomigration (which is a transport phenomenon where atoms move from the hot and to the cold end of the solder joint, or vice versa, due to the temperature difference) as shown in a review study [6].

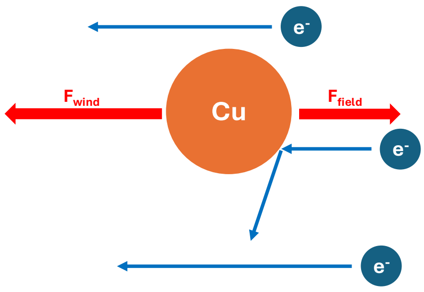

Fig. 1. Forces acting on an atom during current conduction

According to [30], [31], thermomigration may both accelerate or impede electromigration. The large amount of Joule-heat generated may also raise the temperature high enough so that it causes mechanical strain in the solder joint [32], [33], or in other joints of the DUT in for example the case of a BGA package [34]. The high mechanical stress may also cause an atomic flux [32], [35]. The total flux during electromigration is presented in (2).

$$J = J_{ch} + J_{bs} + J_{em}$$

$$J = -C\Omega \frac{D}{kT}\frac{\partial\sigma}{\partial x} - D\frac{\partial C}{\partial x} + C\frac{D}{kT}Z^{*}e\rho j \qquad (2)$$

Where C is the chemical concentration, Ω is atomic volume, k is Boltzmann's constant, T is the absolute temperature, $\partial\sigma/\partial x$ is the stress gradient, D is the diffusivity, Z^* is the effective charge number, e is the electron charge, ρ is the resistivity and j is the current density. From this equation electromigration tendency of solder joints depends greatly on material composition (through the effective charge number, resistivity and diffusivity), temperature and current density. Changing the parameters describing atomic fluxes in the joint could be an effective way to prevent electromigration damage.

C. Mean-time-to-failure (MTTF)

Electromigration is a significant reliability concern for small chip applications. The electromigration phenomena have been shown to exist for various package types, such as QFNs [36], [37], BGAs [34], [38], [39] and chip resistors [9]. Black's equation [12] was published to evaluate the MTTF of metal interconnects in semiconductor chips, however it is still used today to evaluate the electromigration lifetime of solder joints [33], [40], [41], [42]. Black's equation is shown in (3):

$$MTTF = \frac{A}{j^n}\exp\left(\frac{E_a}{kT}\right) \qquad (3)$$

Where A is a cross section dependent constant, j is the current density, n is the current exponent, E_a is the activation energy, k is Boltzmann's constant and T is the absolute temperature. The value of n was initially determined by Black to be $n = 2$, however for solder joints, the value is typically *0,4…2,23* [1], [35], [41], while some recent works also found larger values, such as $n = 7{,}72$ in [40]. The activation energy for Black's equation is around *0,7-0,8 eV* [1], [33], [43] for SAC solder, but its exact value depends on the type of solder used. The use of different solder materials can increase or decrease activation energy significantly [33], [40], [41]. It seems that the constants for Black's equation in case of solder joints depend largely on the structure, composition and process parameters of manufacturing of the joint, and on the testing environment, for example the amount of Joule-heating.

While the equation has been used since its publication, it has been shown in recent years that it is not always accurate in predicting the failure time of solder joints subjected to electromigration [41], [44], [45]. This could be due to the existence of factors beyond those that Black initially investigated in Al lines, such as the accelerating effect of Joule-heat. Several sources, such as [45], [46] have modified Black's equation to improve its predictive ability for solder joints. Equations (4) and (5) show modifications by different methods. Other MTTF models have also been proposed, such as in [47], [48].

Equations (4) (taken from [45]) shows a modified version of Black's equation, where the added variables are *c*, which is a dimensionless constant to account for current crowding, and *ΔT*, which is the temperature rise from Joule-heating. In (5) (taken from [46]) the accelerating factor from the current density and Joule-heating are considered by incorporating the current density into the exponent, for the specific case of a Cu pillar leaded solder bump. The details of the modelling can be found in [46].

$$MTTF = \frac{A}{(cj)^n} \exp\left(\frac{E_a}{k(T + \Delta T)}\right) \qquad (4)$$

$$MTTF = \frac{A}{j^n} \exp\left(\frac{E_a}{k\left(T + \frac{91j^2}{24 - 0,42j^2}\right)}\right) \qquad (5)$$

The modified versions of Black's equation show improved predictive power for the given applications and test cases [1], [45], [46], however it is questionable if they are generally applicable. Other methods for modelling component reliability are also being considered, for example, Sun et al. [42] attempted to create a reliability model for BGA components, based on a k-out-of-N system of solder joints, where the failure of N – k solder joints out of N is the failure condition, and the probabilistic failure of the solder joints is used to model the MTTF of a BGA component. The model in [42] is based on Black's equation and Monte Carlo simulations.

III. Failure modes of electromigration

A. DC current stressing

During electromigration, atoms are being transported through the solder joint. Due to this, several failure modes may arise. There are several processes during EM, which may cause that failure: 1) atomic diffusion through the solder joint to the anodic interface 2) IMC growth inside the solder and at the interfaces decreasing mechanical strength 3) Cu dissolution from pads 4) void formation and cracking.

High current density in solder joints causes the migration of atoms in the solder. During electromigration Sn, Cu, Bi and Pb atoms are transported through the Sn matrix. These atoms may react with the Sn in the matrix, forming IMC in the solder joint. IMC growth is higher along the c-axis of the Sn grains, and the failure speed is increased as well [18], [49], this is because the diffusion in the Sn matrix is much faster along the c-axis of the grains, particularly for Cu [50]. The IMC growth is also high at the anodic Cu/solder interface of the solder joint. IMC thickness of the cathodic interfaces increases during electromigration, however multiple studies suggest, that after reaching a critical thickness, the IMC thickness will begin to decrease [5], [8], [51] due to a change in the atomic fluxes, and the reaction speed difference between the dissolution of the interfacial IMC and the formation reaction of the IMC [8], [51]. The typical IMC formed during electromigration are: Cu6Sn5, Cu3Sn in SAC and Sn-Bi solders [6]. The typical IMC formed in Sn-Pb solders is Cu_6Sn_5 as well [52]. The use of dopants or different surface finishes could influence the type of IMC formed [36], [53]. Often a polarity effect is documented, where the anode interface will form a much thicker IMC layer than the cathode interface [4], [36], [54], [55]. This is shown in Fig. 2.

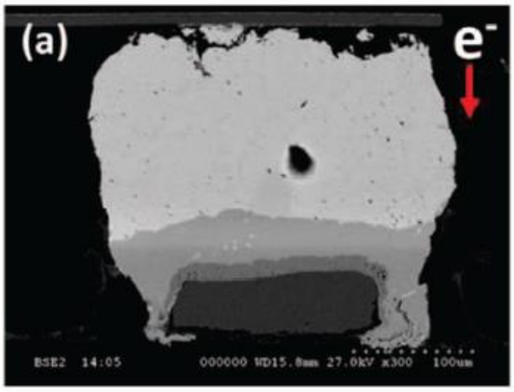

Fig. 2. Solder joint with polarity effect [49]. Crack formation at the cathode accompanied by significant IMC formation at the anode.

Under electrical current load, electrons enter the solder joint at the cathode and exit the solder joint at the anode. In many cases, such as BGA and QFN components, it was shown that the Cu/solder interface of the solder joint is the point where maximal current stress is accumulated due to geometrical constraints [22], [56]. The locally high current stress at the cathode interface may lead to Cu being removed from the lattice, and diffusion through the IMC layer into the solder joint. The vacancy created by the solder joint will either be filled by Sn or IMC in liquid-solid interaction [33], [40], or Kirkendall-voids may begin to form [1], [7], [8], [49]. Many studies have shown that the void formation increases the resistance of the solder joint. As current is forced into a smaller cross section, the local current density is increased, which leads to increased Cu dissolution and void formation, along with higher Joule-heating. At a critical void density, the voids will coalesce into larger voids, until finally a crack forms and the solder joint fails [57]. In some cases, the high current density even causes local melting of the solder joint, leading to a liquid-solid electromigration instead of solid-solid electromigration, accelerating failure even further [4], [29], [40]. Fig. 3 shows the cross-section SEM image of a solder joint failed due to electromigration.

The existence of a thick IMC and voids will lower the mechanical strength of the joint [3], [54], [58], [59], [60], which could cause cracking due to mechanical load [59], [60]. This is suggested in [32], where authors have shown in FEM simulation that BGA solder balls will fail at the corner of the chip, where mechanical strain is maximal. The point of failure is either the point of maximal mechanical strain [33], [39], or the point of maximal current density [1], [40], but the two points also often coincide, for example, the corner of a BGA solder bump is often both the point of maximum current density and mechanical strain.

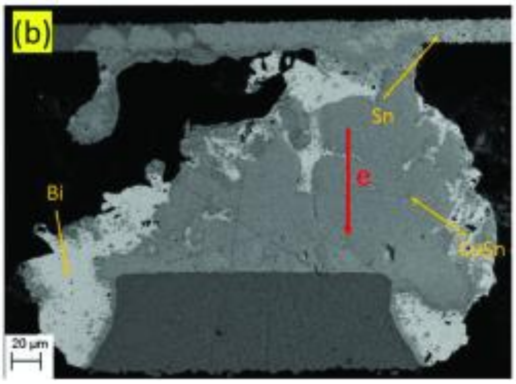

Fig. 3. Solder joint failure due to electromigration [2].

B. AC current stressing

Under DC bias, electrons enter the joint through the cathode of the solder joint and exit through the anode. Electron wind force acts from the cathode to the anode, leading to the dissolution of cathode side Cu pad and IMC. Due to the migration of Cu atoms to the anode, IMC on the anode side thickens, leading to an increase in resistance and mechanical strain in the joint. On the other hand, the cathode forms Kirkendall-voids, which lead to increased current crowding, eventually causing high enough temperatures to locally melt the solder joint. The voids coalesce into cracks, causing failure of the joint. Under load, it could be argued that the reversing current direction could cause a self-healing process in the joint, where during the reversed period, the atomic fluxes due to electromigration are reversed, causing a reduction of overall atomic transport in any direction, by opposing fluxes acting against each other, lengthening the lifetime of the solder joint [61]. Alternating current, as well as pulsed DC current could have longer failure times than DC current. An assumption is that under pulsed DC operation, the MTTF of the samples stressed with a pulsed signal would be proportional to the MTTF of samples stressed under DC, by *100/D*, where *D* is the duty factor of that pulsed DC current [62]. This would mean that a pulsed load increases the MTTF, as electromigration damage can only occur during the on time.

In [62], Kim et al. conducted a study of the behaviour of WLCSP BGA solder joints under pulsed DC current load. The solder used was SAC. They applied a 0,1 Hz current signal, with different duty factors. According to [47], the MTTF would be longer for pulsed DC condition, assuming that electromigration damage can only occur during the „on" time of the signal. However, Kim et al. [62] found that in the case of low frequency pulsed current, at $D = 0,75$, the lifetime of the samples was reduced. They also found that lower duty factors increase the electromigration life-time significantly, which could be due to less time being spent in the electromigration process, and a relaxation process happening during the „off" times. The existence of such a relaxation process in IC conductor lines is suggested in [63].

AC testing was done in [64] on Sn-58Bi BGA solder joints, with square wave current load. Samples were tested at 25 Hz, 50 Hz, 100 Hz and 250 Hz. The samples showed IMC growth, however, unlike for DC loading, random IMC growth inside the solder joint was also observed. The authors attribute the polar IMC growth to thermomigration due to high amounts of Joule-heating and the non-polar growth inside the solder joint to electromigration. Higher frequency and higher duty cycle seemed to indicate earlier failure, however shear strength decrease observed on all loaded samples was not correlated with loading frequency.

Kim et al. [61] did a similar study on SAC solder bumps, where they also found that a higher frequency causes earlier failure and that IMC would form more in the middle of the solder joint than at the interfaces. They also observed anisotropic, dendritic growth of IMC. They found that a higher duty cycle causes earlier failure for samples tested at a low frequency, but at a higher frequency, the lifetime does not depend on the duty cycle. They also saw that at low frequencies, a symmetrical duty cycle creates longer lifetimes than asymmetrical duty cycles, suggesting what is referred to in the paper as a self-healing phenomenon. Self-healing phenomenon in this case means the alternating direction of atomic fluxes lessening the overall material transport in each direction. [65] shows similar results, where applying 1 Hz, 50 % square signal with the same current density as the reference DC signal would produce only ~20 % of the resistance growth compared to the DC stress, significantly extending MTTF, even though a similar RMS load was applied. [66] also suggests the existence of a self-healing process, and they also show that higher frequency alternating loads lead to reduced MTTF, which could also be a result from increasing current densities due to skin-effect.

The above studies highlight that the electromigration phenomena in the case of pulsed DC currents or AC currents is not completely understood, further research in the field is necessary.

IV. Evolution of different solder types under electrical load

A. *Sn-Pb solder joints*

While most industries are now prohibited from using leaded solders, regulations such as the RoHS directive of the European Union still allow the use of Sn-Bi solders in some applications. Therefore, the electromigration behaviour of Sn-Bi solder joints is still relevant. In Sn-Bi solders, mainly Cu_6Sn_5 and Cu_3Sn are formed. At low temperatures, diffusion is dominated by Sn, while at high temperatures, the main diffusion species becomes Pb [15], [44]. During electromigration, besides IMC growth and void formation, a Pb-rich areas may also form at the anode of the solder joints [14], [67], [68] The publication by Li et al. [14] explored electromigration behaviour of Sn-37Pb solder joints under high current load and thermal cycling. They found that temperature cycling between -192 and 120 °C degrees accelerated electromigration behaviour significantly. A large amount of Pb atoms accumulated at the anode side of the joint, and an Sn-rich are observed at the cathode side. Cracks formed at the corners of the solder joints, where the thermal and electrical strain were both maximal. The failure of the solder joints in this case was mostly credited to thermomechanical strain. The electromigration damage accelerated by high temperature or thermal cycling in the Sn-37Pb solder joints is consistent with literature on other types of solders [56], [59], [69].

B. *SAC solder joints*

SAC (Sn-Ag-Cu) is widely used in the PCB manufacturing industry. It is a solder paste with many different variants, for example SAC305 (Sn-3.0Ag-0.5Cu) or SAC705 (Sn-7.0Ag-0.5Cu. The evolution of the solder joint under current load should therefore be investigated.

The diffusion speed of Cu in Sn is higher than Sn’s [20], making Cu the primary diffusion species during SAC electromigration. In the case of SAC solder, Cu to be transported through the solder matrix can come from multiple places: the cathode pad of the solder joint, the dissolution of the interfacial IMC layer and the Cu content in the solder joint itself. As a result of the Cu transport, IMC at the anode interface grows, while the cathode is documented to grow until a critical thickness is reached, then it begins to decrease [5]. The decrease in thickness could be due to the cathode IMC providing a diffusion barrier for atoms of the pad, leading to a reduced atomic flux from electromigration.

Li et al. [5] did a study of SAC305 BGA bumps. The samples were loaded at 2×104 A/cm2 current density and cycled between -196 °C and 150 °C. The samples showed polar IMC growth: anode side IMC increased in thickness, while cathodic IMC showed decrease in thickness. Cracking happened at the corner of the solder joint, where the electron flow enters the joint. The electromigration damage was accelerated compared electromigration test only. While void formation could be an important source of the crack formation, the authors identified the failure mechanism as the CTE mismatch caused by the Joule-heating and mechanical stress from the current combined with thermal cycling. The accelerating effect on electromigration of thermal cycling is also shown in [56], [59], [69]. Sources such as [1], [8], [40] show the IMC growth, voiding and fracture behaviour from electromigration only.

C. *Sn-Bi solder joints*

Sn-Bi solders are of interest in manufacturing, due to their lower melting point (~150 °C), allowing for the low-temperature processing of sensitive materials, such as semi-conductors requiring low temperature, or substrates such as PLA-based substrates. Under current load, Sn-Bi solder, like its SAC or Sn-Bi counterparts exhibits several electromigration phenomena: IMC growth, particularly at the anode, void nucleation and cracking, Cu dissolution, phase segregation resulting in a Bi-rich layer at the anode and an Sn-rich layer at the cathode [2], [27], [70], [71]. During electromigration testing the resistance of Sn-Bi solder joints increases. The initial resistance increase is attributed to the formation of the Bi-rich layer, which due to Bi's higher resistance begins to dominate the resistance of the solder joint [71]. The resistance increase during later parts of testing is attributed to void nucleation and crack formation [16]. Additionally, Bi is more rigid than Sn. The aggregation of a Bi-rich layer at the anode leads to creation of strain in the solder matrix [72], and the higher rigidity of the Bi-rich layer compared to the rest of the solder joint may reduce the mechanical strength of the joint [27].

Singh et al. [16] did a study on the electromigration behaviour of Sn-58Bi solder joints. The study was done at multiple temperatures (60, 80 and 100 °C), and with multiple surface finishes. Their results showed that the Sn-58Bi solder joints underwent a 3-stage resistance increase: 1.) resistance decrease due to phase coarsening 2.) linear increase due to continuous Bi-layer formation and growth 3.) parabolic growth due to slowdown of diffusion because of Bi depletion in the solder joint. The initial decrease in temperature is the result of the fine microstructure coarsening under current load. The initial resistance decrease is also documented in [17], [73], and the phase coarsening behaviour of Sn-Bi is documented in [29]. The phase segregation of Bi and Sn is shown in Fig. 4.

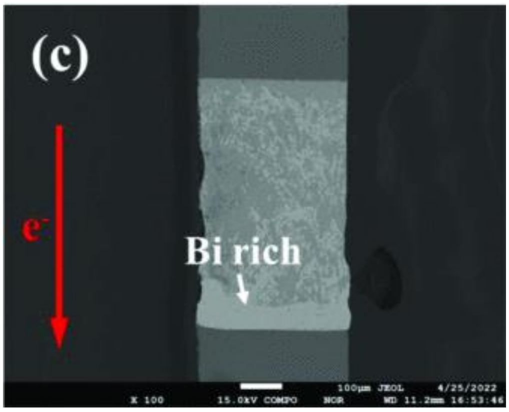

Fig. 4. Bi-rich layer in electromigration stressed Sn-38Bi sample [71]

V. Conclusion

In this review, the literature on electromigration of solder joints was presented. It was shown that the main failure modes of electromigration are IMC thickening, void nucleation at the cathode and Cu dissolution. The IMC thickening and void nucleation lead to an increase in resistance, while the voids also increase current crowding and therefore the temperature of the solder joint. The increased temperature may cause the local melting of the solder joint. The local melting leads to liquid-solid electromigration interaction and the failure of the solder joint in the formation of open circuits. Mechanical strain could also become large enough to cause cracking of the solder joints. Different solder materials show different electromigration behaviours, for example, in Sn-Bi, Sn-Bi and SAC solders, the main diffusion species are Pb, Bi and Cu respectively. During electromigration, Pb- and Bi-rich layers form at the anode, while Sn-rich layer will form at the cathode of Sn-Bi and Sn-Bi solder joints. The Bi-rich layer has higher electrical resistance and rigidity, leading to the overall resistance increase of the solder joints and higher possibility of mechanical failure. It is also shown, that due to the body-centered tetragonal structure of the Sn matrix, diffusion happens faster along the c-axis of grains. Therefore, if the grain structure of the solder joint is such that the c-axis of the Sn grains are oriented towards the current flow direction, the electromigration effects are accelerated, and formation of IMC along the grain boundaries can be seen. As device and interconnect sizes continue to decrease, it becomes more important to prevent electromigration in solder joints. The further the development of the field and understanding of underlying mechanisms is important to improve electromigration robustness and the reliability of solder interconnections, and therefore PCB assemblies in the future.

Acknowledgment

The project supported by the Doctoral Excellence Fellowship Programme (DCEP) is funded by the National Research Development and Innovation Fund of the Ministry of Culture and Innovation and the Budapest University of Technology and Economics.

The research was supported by DESIRE4EU HORIZON-EIC-2023-PATHFINDERCHALLENGES-01-04 Project No. 101161251.

References

[1] J. Zhang, et al. ‘Electromigration Reliability of SnAgCu…’, IEEE ICEPT, 2024, pp. 1–6. doi: 10.1109/ICEPT63120.2024.10668659.

[2] J. Xu, et al. ‘A Comprehensive Study of Electromigration…’, IEEE ECTC, 2020, pp. 284–289. doi: 10.1109/ECTC32862.2020.00054.

[3] S. Zhang et al., ‘Investigation on electromigration failure behavior of SAC305/SnPb micro-hybrid solder joints…’, Materials Letters, vol. 377, p. 137394, 2024, doi: 10.1016/j.matlet.2024.137394.

[4] J. Huang et al., ‘Polarity effect of interfacial intermetallic compounds of BGA structure…’, Intermetallics, vol. 168, p. 108252, 2024, doi: 10.1016/j.intermet.2024.108252.

[5] S. Li et al., ‘Current-induced solder evolution and mechanical property…’, Journal of Alloys and Compounds, vol. 970, p. 172519, 2024, doi: 10.1016/j.jallcom.2023.172519.

[6] P. Zhang, et al., ‘New challenges of miniaturization of electronic devices…’, Materials & Design, vol. 192, p. 108726, 2020, doi: 10.1016/j.matdes.2020.108726.

[7] Y.-W. Chang et al., ‘Electromigration Mechanism of Failure…’, Sci Rep, vol. 7, no. 1, p. 17950, 2017, doi: 10.1038/s41598-017-06250-8.

[8] J.-Y. Park, et al., ‘Electromigration reliability of Sn–3.0Ag–0.5Cu/Cu–Zn solder joints’, J Mater Sci: Mater Electron, vol. 30, no. 8, pp. 7645–7653, 2019, doi: 10.1007/s10854-019-01080-y.

[9] D. Straubinger, et al., ‘Impact of electromigration and isothermal ageing…’, Journal of Materials Research and Technology, vol. 21, pp. 308–318, 2022, doi: 10.1016/j.jmrt.2022.09.048.

[10] Y.-H. Liao et al., ‘High dislocation density of tin induced by electric current’, AIP Advances, vol. 5, no. 12, p. 127210, 2015, doi: 10.1063/1.4937909.

[11] F.-Y. Ouyang, et al., ‘Effect of electromigration induced joule heating and strain…’, Materials Chemistry and Physics, vol. 136, no. 1, pp. 210–218, 2012, doi: 10.1016/j.matchemphys.2012.06.054.

[12] J. R. Black, ‘Electromigration—A brief survey and some recent results’, IEEE Trans. Electron Devices, vol. 16, no. 4, pp. 338–347, 1969, doi: 10.1109/T-ED.1969.16754.

[13] M. N. Bashir and A. S. M. A. Haseeb, ‘Grain size stability of interfacial intermetallic compound…’, J Mater Sci: Mater Electron, vol. 33, no. 17, pp. 14240–14248, 2022, doi: 10.1007/s10854-022-08352-0.

[14] S. Li et al., ‘The microstructure evolution and failure mechanism of Sn37Pb solder joints…’, Materials Today Communications, vol. 36, p. 106651, 2023, doi: 10.1016/j.mtcomm.2023.106651.

[15] G. A. Rinne, ‘Electromigration in SnPb and Pb-free solder bumps’, IEEE ECTC, 2004, pp. 974–978. doi: 10.1109/ECTC.2004.1319457.

[16] P. Singh et al., ‘Electromigration in Eutectic Tin-Bismuth…’, IEEE ECTC, 2024, pp. 1433–1438. doi: 10.1109/ECTC51529.2024.00233.

[17] P. Singh et al., ‘Comparing Electromigration in Tin-Bismuth…’, IEEE ICEP, 2024, pp. 55–56. doi: 10.23919/ICEP61562.2024.10535675.

[18] Y.-A. Shen and C. Chen, ‘Effect of Sn grain orientation…’, Scripta Materialia, vol. 128, pp. 6–9, 2017, doi: 10.1016/j.scriptamat.2016.09.028.

[19] Y.-C. Huang et al., ‘Crystalline Orientation Effect…’, IEEE Trans. Electron Devices, vol. 71, no. 9, pp. 5784–5787, 2024, doi: 10.1109/TED.2024.3429478.

[20] C. Li, et al., ‘Effect of βSn grain orientations…’, Materials Characterization, vol. 215, p. 114227, 2024, doi: 10.1016/j.matchar.2024.114227.

[21] Z. Fan et al., ‘Effect of bump shapes…’, IEEE ICEPT, 2021, pp. 1–6. doi: 10.1109/ICEPT52650.2021.9568080.

[22] Y. Li, Y. C. Chan, and X. Zhao, ‘Effect of pad shape…’, IEEE ESTC, Sep. 2014, pp. 1–5. doi: 10.1109/ESTC.2014.6962849.

[23] Y.-B. Park, et al., ‘Solder Volume Effect…’, IEEE Trans. Compon., Packag. Manufact. Technol., vol. 10, no. 10, pp. 1589–1593, 2020, doi: 10.1109/TCPMT.2020.3005644.

[24] Y. Kim, et al., ‘Fracture behavior of Cu-cored solder joints’, J Mater Sci, vol. 46, no. 21, pp. 6897–6903, 2011, doi: 10.1007/s10853-011-5654-x.

[25] C. Fleshman, et al., ‘Phase identification and interface evolution…’, Materials Letters, vol. 275, p. 128104, 2020, doi: 10.1016/j.matlet.2020.128104.

[26] I. Wodak et al., ‘Impact of Fe-NPs doped flux on electromigration…’, IEEE SIITME, 2024, pp. 370–373. doi: 10.1109/SIITME63973.2024.10814758.

[27] W. Chen, et al., ‘Effect of electromigration on microstructure…’, Sci Rep, vol. 14, no. 1, p. 15693, 2024, doi: 10.1038/s41598-024-66681-y.

[28] M. N. Bashir et al., ‘Effect of Zn nanoparticle-doped flux…’, J Mater Sci: Mater Electron, vol. 34, no. 4, p. 321, 2023, doi: 10.1007/s10854-022-09722-4.

[29] H. Zhuang, et al., ‘Electromigration in Power Devices…’, Journal of Microelectronics and Electronic Packaging, vol. 18, no. 1, pp. 1–6, 2021, doi: 10.4071/imaps.1377365.

[30] M. F. Abdulhamid, et al., ‘Thermomigration Versus Electromigration…’, IEEE Trans. Adv. Packag., vol. 32, no. 3, pp. 627–635, 2009, doi: 10.1109/TADVP.2009.2018293.

[31] W. Tian, et al., ‘Simulation Research on Electromigration…’, IEEE ICEPT, 2021, pp. 1–5. doi: 10.1109/ICEPT52650.2021.9568130.

[32] Y. Xuan, et al., ‘Reliability Analysis and Comparison…’, IEEE IPFA, 2024, pp. 1–8. doi: 10.1109/IPFA61654.2024.10690969.

[33] Y. R. Kim, et al., ‘Effects of UBM Thickness…’, IEEE IRPS, 2020, pp. 1–5. doi: 10.1109/IRPS45951.2020.9129337.

[34] K. N. Tu and A. N. Gusak, ‘Mean-Time-To-Failure Equations…’, IEEE Trans. Compon., Packag. Manufact. Technol., vol. 10, no. 9, pp. 1427–1431, 2020, doi: 10.1109/TCPMT.2020.3003003.

[35] F. Wang, et al., ‘Electromigration behaviors in Sn–58Bi…’, J Mater Sci: Mater Electron, vol. 29, no. 24, pp. 21157–21169, 2018, doi: 10.1007/s10854-018-0264-x.

[36] Y.-C. Liu et al., ‘Electromigration Failure Study…’, IEEE IMPACT, 2024, pp. 219–222. doi: 10.1109/IMPACT63555.2024.10818931.

[37] M.-C. Chiu, et al., ‘Applications of Ni and Ag metallizations…’, Surface and Coatings Technology, vol. 484, p. 130828, 2024, doi: 10.1016/j.surfcoat.2024.130828.

[38] F. Zhang, et al., ‘Study on the Differences of Electromigration Life…’, IEEE ICEPT, 2022, pp. 1–3. doi: 10.1109/ICEPT56209.2022.9872717.

[39] S. Chen, et al., ‘The Reliability of Complex Printed Circuit Board…’, IEEE ICEPT, 2024, pp. 01–06. doi: 10.1109/ICEPT63120.2024.10668716.

[40] X. Wu, et al., ‘Identification of electromigration failure…’, IEEE ICEPT, 2022, pp. 1–5. doi: 10.1109/ICEPT56209.2022.9873363.

[41] M. Lu and E. G. Colgan, ‘Electromigration Kinetics…’, IEEE ECTC, 2024, pp. 1848–1852. doi: 10.1109/ECTC51529.2024.00309.

[42] F.-B. Sun and Y. Sun, ‘Quantify Device EM Reliability…’, IEEE RAMS, 2022, pp. 1–7. doi: 10.1109/RAMS51457.2022.9893934.

[43] W. J. Choi, et al., ‘Mean-time-to-failure study…’, Journal of Applied Physics, vol. 94, no. 9, pp. 5665–5671, 2003, doi: 10.1063/1.1616993.

[44] H. Gan, et al., ‘Electromigration in solder joints and solder lines’, JOM, vol. 54, no. 6, pp. 34–37, 2002, doi: 10.1007/BF02701847.

[45] W. J. Choi, et al., ‘Mean-time-to-failure study…’, Journal of Applied Physics, vol. 94, no. 9, pp. 5665–5671, 2003, doi: 10.1063/1.1616993.

[46] S. Chen, et al., ‘Black equation of the electromigration lifetime…’, IEEE ICEPT, 2020, pp. 1–4. doi: 10.1109/ICEPT50128.2020.9202871.

[47] W. Yao and C. Basaran, ‘Electromigration damage mechanic…’, Computational Materials Science, vol. 71, pp. 76–88, 2013, doi: 10.1016/j.commatsci.2013.01.016.

[48] W. Yao and C. Basaran, ‘Electromigration analysis of solder joints under ac load…’, Journal of Applied Physics, vol. 111, no. 6, p. 063703, 2012, doi: 10.1063/1.3693532.

[49] Y. R. Kim et al., ‘Relationship Between the Grain Orientation…’, IEEE ECTC 2021, pp. 2334–2339. doi: 10.1109/ECTC32696.2021.00365.

[50] B. F. Dyson, et al., ‘Interstitial Diffusion of Copper in Tin’, Journal of Applied Physics, vol. 38, no. 8, pp. 3408–3408, 1967, doi: 10.1063/1.1710127.

[51] F. Zhang, et al., ‘Effect of Electromigration on Interfacial Reaction…’, IEEE ICEPT, 2021, pp. 1–4. doi: 10.1109/ICEPT52650.2021.9568172.

[52] F. Wang, et al., ‘Interfacial behaviors of Sn-Pb, Sn-Ag-Cu…’, Microelectronics Reliability, vol. 73, pp. 106–115, 2017, doi: 10.1016/j.microrel.2017.04.031.

[53] C.-W. Chen, et al., ‘Current induced segregation…’, Intermetallics, vol. 85, pp. 117–124, 2017, doi: 10.1016/j.intermet.2017.02.012.

[54] X. J. Wang, et al., ‘Effects of Current Stressing on Shear Properties…’, Journal of Materials Science & Technology, vol. 26, no. 8, pp. 737–742, 2010, doi: 10.1016/S1005-0302(10)60116-8.

[55] Y. Yao, et al., ‘Coupling Effect of Electromigration…’,IEEE ICEPT, 2023, pp. 1–4. doi: 10.1109/ICEPT59018.2023.10492376.

[56] S. Chen, et al., ‘The Reliability of Complex Printed Circuit Board…’, IEEE ICEPT, 2024, pp. 01–06. doi: 10.1109/ICEPT63120.2024.10668716.

[57] Q. Liu, et al., ‘SEM study on the mechanism of electromigration…’, IEEE ICEPT, 2023, pp. 1–6. doi: 10.1109/ICEPT59018.2023.10492130.

[58] F. Ren, et al., ‘Electromigration induced ductile-to-brittle…’, Applied Physics Letters, vol. 89, no. 14, p. 141914, 2006, doi: 10.1063/1.2358113.

[59] S. Zhang, et al., ‘Accelerative reliability tests for Sn3.0Ag0.5Cu…’, Microelectronics Reliability, vol. 120, p. 114094, 2021, doi: 10.1016/j.microrel.2021.114094.

[60] A. T. Osmanson et al., ‘Current Crowding and Stress…’, IEEE IWLPC, 2020, pp. 1–8. doi: 10.23919/IWLPC52010.2020.9375862.

[61] Y. Ram Kim, et al., ‘Study of Failure and Microstructural Evolution…’, IEEE ECTC, 2022, pp. 1153–1157. doi: 10.1109/ECTC51906.2022.00186.

[62] Y. R. Kim, et al., ‘Study of Electromigration Failure…’, IEEE ECTC, 2020, pp. 723–728. doi: 10.1109/ECTC32862.2020.00119.

[63] I. J. Ringler and J. R. Lloyd, ‘Stress relaxation in pulsed DC…’, AIP Advances, vol. 6, no. 9, p. 095118, 2016, doi: 10.1063/1.4963669.

[64] P. Zhu et al., ‘Electromigration Behavior of Cu/Sn-58Bi/Cu…’, IEEE ICEPT, 2024, pp. 01–05. doi: 10.1109/ICEPT63120.2024.10668721.

[65] J. Xu, et al., ‘Research on Electromigration Behavior…’, IEEE ICEPT, 2021, pp. 1–4. doi: 10.1109/ICEPT52650.2021.9568121.

[66] W. Yao and C. Basaran, ‘Damage mechanics of electromigration…’, International Journal of Damage Mechanics, vol. 23, no. 2, pp. 203–221, 2014, doi: 10.1177/1056789513488396.

[67] Jae-Young Choi, et al., ‘Electromigration behavior of eutectic SnPb solder’, IEEE Advances in Electronic Materials and Packaging, 2001, pp. 417–420. doi: 10.1109/EMAP.2001.984020.

[68] H. Cao, et al., ‘Research on Evolution Behaviors…’, IEEE ICEPT, 2018, pp. 891–894. doi: 10.1109/ICEPT.2018.8480550.

[69] Z. Shen, et al., ‘Synergistic Effect of Current Stressing…’, IEEE ICEPT, 2023, pp. 1–5. doi: 10.1109/ICEPT59018.2023.10492344.

[70] C. Jois, et al., ‘Fabrication and Testing of In-Line Structures…’, IEEE ECTC, 2024, pp. 1–4. doi: 10.1109/ECTC51529.2024.00368.

[71] L. Li, et al., ‘Electromigration-induced failure behavior…’, IEEE ICEPT, 2023, pp. 1–5. doi: 10.1109/ICEPT59018.2023.10491977.

[72] M. B. Kelly, et al., ‘Electromigration in Bi-crystal pure Sn…’, Journal of Alloys and Compounds, vol. 818, p. 152918, 2020, doi: 10.1016/j.jallcom.2019.152918.

[73] P. Singh et al., ‘In Situ Study of Electromigration…’, IEEE Pan Pacific, 2024, pp. 1–6. doi: 10.23919/PanPacific60013.2024.10436519.