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ELECTROMIGRATION EFFECTS IN SOLDER JOINTS DOPED WITH FE NANOPARTICLES

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Absztrakt

Az elektronikai technológiai fejlesztések egyik fő célja az elmúlt évtizedekben az egy modulban megvalósított funkciók számának növelése volt. Az integráltsági fok növelése érdekében a gyártók egyre kisebb komponenseket alkalmaznak készülékek tervezése során, ideértve a PCB-ket (Printed Circuit Board, nyomtatott áramkört lemez) is. A PCB-ken használt chipméretű komponensek, mint az ellenállások vagy a kondenzátorok gyakran 0402-es vagy kisebb méretűek ($1 \times 0,5$ mm).

Bár az alkatrészek mérete jelentősen csökkent az elmúlt évtizedekben, a terhelésük nem követte ezt a tendenciát. Működés közben, azonos terhelés mellett a kisebb méretű alkatrészek akár jelentősen nagyobb áramsűrűségnek lehetnek kitéve, ráadásul nagyobb a valószínűsége olyan pontok vagy zónák kialakulásának az alkatrészben vagy kötéseikben, ahol az áramsűrűség lokálisan megnő. A megnövekedett áramsűrűség növeli a hatását az elektromigrációs jelenségeknek [1], az IMC (intermetallic compound, intermetallikus vegyület) rétegek növekedését [2], a Cu felületek zárványosodását [2], és bizonyos esetekben akár a forrasztanyag lokális megömlését [3], vagy újrakristályosodását [4] is okozhatja. Ezeknek a hatásoknak az eredménye lehet az, hogy a forraszkötés aztán idővel ridegebbé válik [5], mely csökkenti az alkatrészek megbízhatóságát és növeli az esélyét a korai meghibásodásoknak. A termomigrációból és elektromigrációból származó hatásokat nehéz elkülöníteni. Ezeknek a terheléseknek, hatásoknak a vizsgálata fontos, a további méretcsökkenéshez szükséges a vizsgálatuk. A nanorészecskék hozzáadása a forrasztanyaghoz egy lehetséges megoldás lehet, amellyel csökkenteni lehet a káros hatásokat [6].

Dolgozatomban a Bércsi Műszaki Egyetemmél közös kutatás részeként, megvizsgálom az elektromigrációs jelenségek hatását egy kontrollált hőmérsékletű, Joule-hő redukált környezetben. A forraszkötések Fe atomokkal adalékoltak 0, 0,5, 1 és 2 wt. % mennyiségekben. 0402 és 0603 méretkódú ellenállások és forraszkötéseik nagy, de gyakorlatban is előforduló árammal (4 A), daisy-chain konfigurációban voltak terhelve 4000 órán keresztül, hogy az elektromigrációs jelenségek fokozott formában legyenek jelen. A dolgozatban fő szerepet kap az IMC rétegek vastagságvizsgálata. A dolgozatban megmutatom, hogy a forraszkötések adalékolása Fe atomokkal alkalmas arra, hogy csökkentsük az elektromigrációs jelenségeket, és az IMC vastagodást.

Abstract

The integration of more functions into a single electrical module has been a driving force of electronics research for the past decades. During this work, electrical components have been reduced in size to allow the fitting of more components onto a single PCB (Printed Circuit Board). While the reduction in size of chip components, such as resistors and capacitors – which are now widely used in case sizes of 0402 (1×0.5 mm) or smaller – has allowed PCBs to incorporate more functions in smaller spaces, it also raises reliability concerns.

While the chip size has been reduced significantly, the load on the chips and therefore the load on the solder joints has not. During operation, smaller case size components loaded with the same current may see current densities that are significantly higher. The smaller joints also have a higher tendency to show current crowding. The increased current density may lead to increased effects of electromigration [1], IMC (intermetallic compound) growth [2], Cu dissolution [2] and in some cases, even localized melting [3], and recrystallization of the solder joint [4]. These effects together can make the solder joints more brittle [5], reducing mechanical stability and shear strength [2], and increasing the likelihood of failure during operation in the field. Electromigration induced IMC growth and thermomigration induced IMC growth – such as localized melting – are not easily distinguishable. It is important to separate these effects and to investigate possible means of reducing the detrimental effects from these phenomena. Adding nanoparticles (NP) may reduce the effects of current stress in the solder joints [6].

In this paper, the electromigration effects are investigated in a temperature controlled, Joule-heat reduced manner. The effect of Fe doping of NPs into the flux before soldering on electromigration and Cu dissolution is investigated. Samples of 0402 and 0603 resistors were stressed in a daisy-chain configuration with high current (4 A), for approximately 4000 h. The samples were doped with Fe NPs in concentrations of 0, 0.5, 1 and 2 wt. %. The effect of NPs on the growth of IMC layers in the solder joints is also investigated. It is shown that some amount of Fe addition to the flux is beneficial to the solder joints, as it suppresses IMC growth and electromigration behaviour.

1 Introduction

The field of electronics technology is one of the fastest growing and developing fields of research in the world. New discoveries and improvements are constantly being made. One of the driving forces of this research has been the need to integrate more functions into a single electrical module. This need resulted in components of these modules being harshly reduced in size. One of these modules is the PCB (Printed Circuit Board), which is used on almost all electronic applications. Chip size components on these PCBs and chips in general have been manufactured in smaller and smaller cases, and nowadays sizes of 0402 ($1 \times 0.5\text{mm}$) or smaller are widely used. While the use of these very small components makes it easier to incorporate more functions onto a single PCB, the use of them gives rise to reliability concerns.

While the chip-size components on PCB boards have reduced in size drastically, the current load on the devices has not. This means that the same current flows through a smaller cross-section, which could make current density increase significantly. The smaller components could also be more prone to current crowding [7], [8], meaning that hot spots could appear, where current density is significantly higher than in other places in the solder joint. The increased current density results in increased load on the component and on the solder joint connecting the component to the PCB both electrically and mechanically. The higher load can produce issues such as Cu pad dissolution [2], [9], [10], migration of atoms to the anode of the joint and thickening of the IMC (Intermetallic Compound) layer [9], [11], void formation on the cathode side of the joint [2], [11], [12]. Some studies have shown that smaller solder joints, such as the ones used in 3D packaging and chip-size packages, can even be fully converted into IMC [11] with sufficient time and current stress. The increased current density can also cause recrystallization of the solder joint [13] and localized melting of the solder [7], the latter of which could exacerbate the IMC issue, since chemical reactions required to form the IMC are faster in the molten state [9], and electromigration behaviour could also worsen, since atoms in a liquid medium require less energy to move than atoms in a solid medium. Due to these effects, the thermomigration and electromigration phenomena are sometimes often appearing together, making it difficult to separate what was caused by which effect. The IMC is more brittle than the solder joint [2], [5], [14], and the voiding can also degrade the mechanical properties of the solder joints. It has been shown that current stress can decrease the shear strength of solder joints significantly [14]. Since the weakening of the solder joint is undesirable from a reliability

perspective, these effects, and methods of protection against them should be thoroughly investigated.

Literature shows that one possible avenue of protecting the joints is by using NP (nanoparticle) dopants, either introduced into the flux [15] before applying the solder paste, or directly into the solder material [16]. The addition of these dopants can make the solder joints less prone to develop thick IMC layers during reflow and makes them more resistant to electromigration induced thickening of the IMC and voiding of the Cu at the cathode side of the joint. The Technical University of Wien has preliminary work in application of Fe NPs in lead-free solder joints, the following work connects on a cooperation between BME ETT and Institute of Chemical Technologies and Analytics, TU Wien.

In this study the behaviour of solder joints doped with Fe NPs has been investigated in a temperature controlled, Joule-heat reduced manner. The samples investigated were 0603 and 0402 resistors in a daisy-chain configuration. The solder samples were doped with 0, 0,5, 1 and 2 wt. % Fe NPs, added to the flux before soldering. The soldered resistors were put into an oven with airflow provided by ventilators and loaded with 4 A current, for 4000 h. The temperature was kept stable after a brief start-up period at ~ 80 °C on the boards themselves, measured using K-type thermocouples, and the temperature of the oven was also monitored, along with the ambient temperature, using BME280 and BME680 sensors and an Arduino Uno R4 Wi-Fi board. The samples were taken out at 1000 h, 2000 h and 4000 h, and were examined by shear-force tests and cross-sectional analysis. This study shows that Fe addition to the solder joint can improve electromigration behaviour and IMC growth behaviour.

At the time of writing of this paper, preliminary parts of this study had already been accepted and presented at the 24th SIITME conference in Romania (16-19 October, Sibiu). This manuscript is a separate work compared to the submitted one with new results and analysis.

2 Literature

Electromigration effects have been the topic of research for decades. While there have been many publications in this area, the phenomenon is still not completely understood. Before delving into the details of this study, I would like to first present a brief overview of the literature. I would like to begin with the definitions necessary for the topic and then move to examples of research that could be important for the work.

2.1 Definitions

2.1.1 Electromigration

The definition for electromigration used in this work is taken from [17]. When current passes through a conductor, the electrons flowing in the material are colliding with the atoms in the solid or liquid medium that is the conductor. During these collisions, momentum and energy is exchanged between the electrons and the atom. If the energy and momentum transferred to the atom is high enough, the atom will begin to move, in the case of for example a crystal structure, the atom will be pushed out of the structure, creating a vacancy. The movement of atoms due to the impact of the electrons is called electromigration, and the force exerted by the electrons upon the atoms is called the electron wind force. The atoms also experience the force of the electric field, which acts in the reverse direction compared to the force from the impact of electrons. The electromigration phenomenon is the result of these two forces and will happen in the direction of the greater force. Figure 2-1 presents this phenomenon.

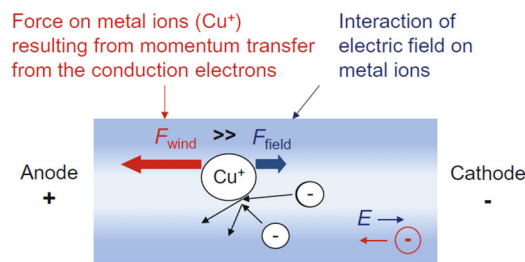


Figure 2-1 – Forces acting on an atom in the crystal structure when current flows in the material [17]

The electron wind force can be estimated by Equation 2-1, according to [9].

$$F_w = Z^* e \rho j$$

Equation 2-1 – Electron wind force [9]

Where Z^* is the effective charge number, e is the electron charge, ρ is the resistivity and j is the current density. The electron wind force F_w is proportional to the current density.

Atomic flux due to electromigration can be expressed as in Equation 2-2:

$$J = J_\sigma + J_{chem} + J_{em} = -C\Omega \frac{D}{kT} \frac{\partial \sigma}{\partial x} - D \frac{\partial C}{\partial x} + C \frac{D}{kT} Z^* e \rho j$$

Equation 2-2 – Atomic flux during electromigration [9]

Where J_σ is the atomic flux from back stress, J_{chem} is the atomic flux due to the concentration of atoms (chemical potential), J_{em} is the atomic flux from electromigration. Ω is the atomic volume, C is the concentration, D is diffusivity, σ is back stress, k is Boltzmann's constant, T is the absolute temperature, e is the electron charge, ρ is resistivity, Z^* is the effective charge number and j is the current density. It is visible from this equation, that the atomic flux of the transport processes in the solid state depends on multiple factors, one of which is the current density.

If there is a large current flow going through a crystal such as a solder joint, more electrons can collide with the atoms. This raises the probability that an atom will be removed from the crystal matrix. When the size of chip components is reduced, from 0603 to 0402, the cross section of the contact is decreased by 2,19x, the current density, assuming a constant current load and uniform distribution, will increase by the same multiplier. The resulting increased load makes it more likely that atoms will be removed from the solder matrix and moved to different areas of the joint, resulting in Cu dissolution, void formation and IMC growth.

2.1.2 Diffusion

When the solder is in the molten state, atoms may flow due to the difference in concentration. The movement of atoms due to a concentration difference is called diffusion. Since the atoms in the solder material are not distributed evenly, there will be a concentration difference, resulting in material transport. When the test vehicle is heated up, the atoms get to a state of higher excitation (higher temperature), resulting in more movement, and therefore faster, more noticeable diffusion. The energy required for the electron wind force to remove the ion from the crystal is also lowered [9], [18]. While diffusion is visible when the solder is in the molten state, it also happens during the operation of the device. For example, Cu atoms from the pad on the PCB are dissolved into the solder matrix during the reflow and operation of the component, and the dissolved Cu particles will move to the anode and form IMC layers there. The dominant process for this movement is bulk diffusion [19] according to the literature.

The definition of bulk diffusion, according to [20] is the following. Bulk diffusion is atomic diffusion within a crystal lattice, which occurs by interstitial or substitutional mechanisms. Interstitial mechanism refers to when the diffusant (in this case the Cu atom) will diffuse between the lattice structure of solder, while in the case of substitutional diffusion, the diffusant atoms can only move by switching places with another atom which is in the lattice. These two mechanisms are shown in Figure 2-2. For substitutional diffusion, point vacancies are often required in the lattice for the diffusing particle to be able to jump to new locations.

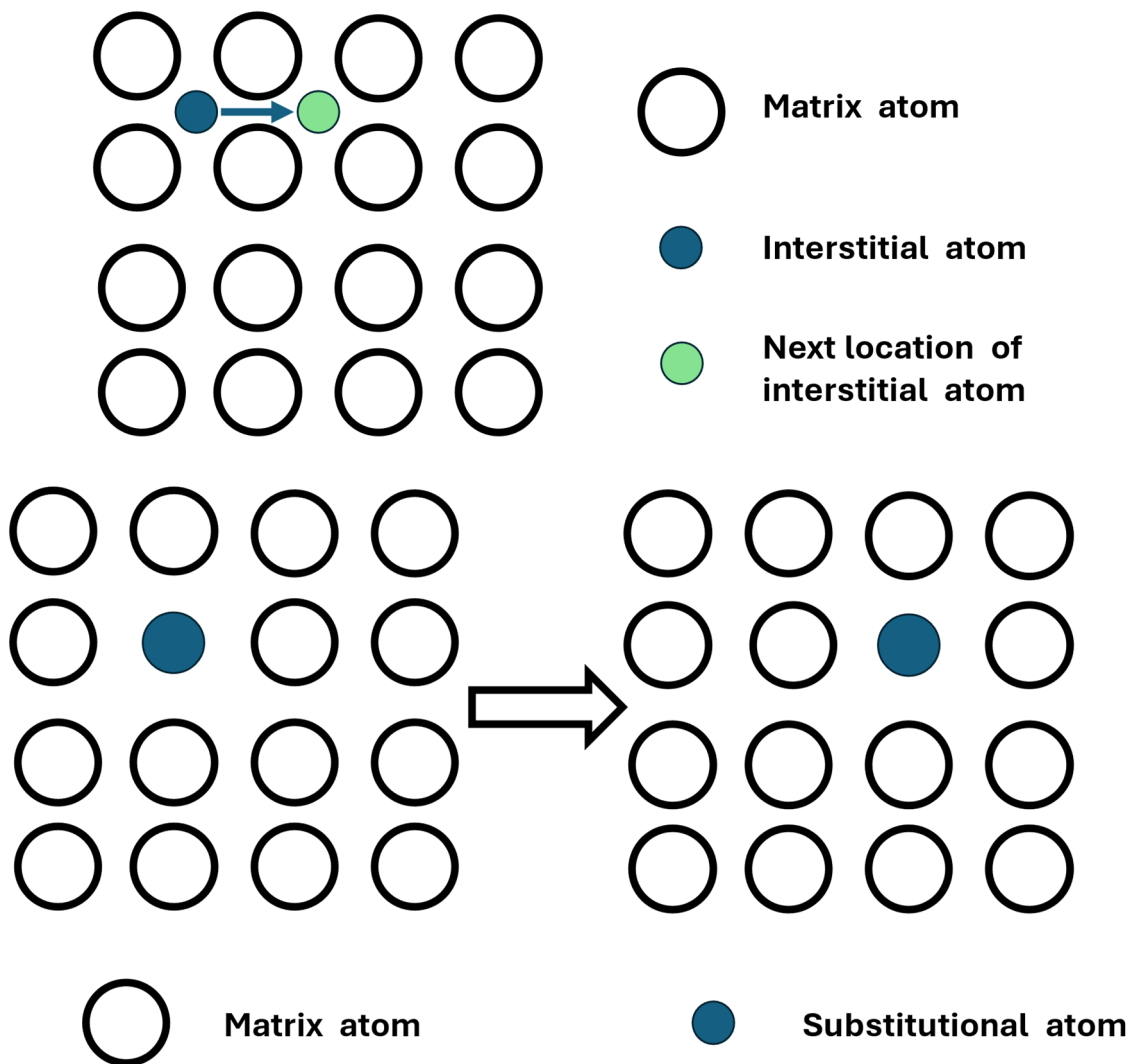


Figure 2-2 – Diffusion mechanisms. Top: interstitial diffusion, bottom: substitutional diffusion

As stated before, literature is pointing to the fact that bulk diffusion is the dominant diffusion mechanism of Cu particles in the solder joint. EM effects and high temperature will lessen the energy required for the Cu to be transported through the joint, and therefore will speed up the diffusion process. It is also possible to reduce the effect of diffusion using tools such as treatment of the solder with NPs.

2.1.3 Recrystallization

During reflow soldering, the solder will crystallize into a solder matrix during the cooling process. When loading the solder joint with large currents, electrons are moving through the matrix, generating heat and exerting force on the ions in the crystal matrix of the solder joint. In these cases, it is possible to cause the recrystallization of the solder matrix [3], [11], [13], [21]. It was shown in [13], [21] that using high current and controlled temperature, it is possible to cause the recrystallization of the solder joint by the current density alone. Liao et al. [21] have shown research, where high current is used to recrystallize the solder joint and then the samples were put into a liquid nitrogen bath to provide rapid cooling and freeze the microstructure. Other papers corroborate his results, showing that recrystallization is possible in the solder joint due to high current [3], [13], [22], [23], [24]. Much like electromigration, the heat generating effect of the current plays a role here as well. The high temperature may increase mechanical stress in the joint and provide the energy required for the recrystallization. In [25] it is shown that thermal cycling can create recrystallization even in the absence of electrical stress. Phase coarsening is also observed in some literature such as [3], [22]. Figure 2-3 shows an example of a solder joint after recrystallization due to current stress. The change in structure is clearly visible. Similar results can be found in for example [3].

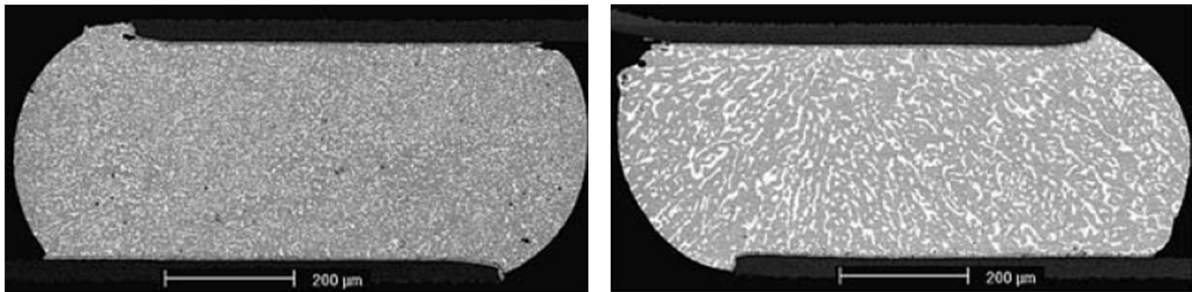


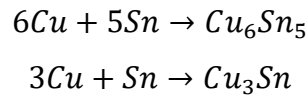
Figure 2-3 – Sn-Pb solder joint recrystallization from current stress. Left: as-reflowed solder bump, right: bump after 600 h current load [22]

It was also shown in [22] that SAC solder may show different behaviour than Sn-Pb solders. IMC layer thickening may also be observed without polarity effects [22], which points to a phenomenon that is not electromigration, where voiding and layer thickening are expected at different sides of the solder joint. Thermomigration shows similar polarized behaviour [12], [26].

2.1.4 Intermetallic compound layer growth

The definition of intermetallic compounds (IMC) according to [27] is the following: when a chemical compound is formed from two or more metallic components in specific proportions, rather than continuously variable proportions, the compound is referred to as an intermetallic compound. Intermetallic compounds generally have small heats of formation compared to salts and polymeric compounds. IMCs exist which melt without decomposition while others will decompose into a liquid state or a solid with a different composition [27]. The properties of intermetallic compounds may be largely different from the properties of the components forming the intermetallic compounds.

During the reflow soldering process, IMC layers are formed in the solder joint due to the presence of different metals (e.g. Cu, Sn, Cu) and high temperature. The metals in the molten solder interact with each other, resulting in the creation of a compound layer. The most common IMC layers in case of SAC305 solder are Cu_6Sn_5 and Cu_3Sn , where the Cu for the reaction is provided by the pad on the PCB and the Sn is provided by the solder material. Of course, in case of other solder materials, for example Sn37Pb, different IMC would form [22]. The reaction equations for the creation of the IMC compounds of SAC solder applied to Cu pads are visible in Equation 2-3:



Equation 2-3 – Reaction equations for IMC formation (Cu_6Sn_5 and Cu_3Sn)

Empirical equations have been developed based on an Arrhenius model to study and predict the IMC growth in the solid state. Two models used as references in this work are shown in Equation 2-4 [28] and Equation 2-5 [29]:

$$x(t) = x_0 + 34130t^{0,336}e^{-\frac{48970}{RT}}$$

Equation 2-4 – IMC growth based on Arrhenius model, parameters for 150 °C aging [28]

$$x(t) = x_0 + 1,05 \cdot 10^{-3}t^{0,58}e^{-\frac{50 \times 10^3}{RT}}$$

Equation 2-5 – IMC growth based on Arrhenius model, parameters for 170 °C [29]

Where $x(t)$ is the IMC layer thickness at time t , t is the reaction time, $x_0 = x(t = 0)$ in μm for Equation 2-4 and m for Equation 2-5.

The formation of the IMC layer during the reflow process is unavoidable due to the nature of the solder materials, but it is also undesirable. The IMC layer is more brittle than the

rest of the solder joint and it creates a mechanical weakness inside the joint. Thicker IMC layers are correlated with lowered shear strength of the component across the literature [2], [5], [14], [30]. The lowered shear strength of the joint can cause more and earlier failure of the solder joint and therefore the electrical module the component is mounted on. This is especially problematic in fields where safety critical systems could be affected, such as the automotive industry, where only a limited range of repair is possible by law.

2.2 Previous works

As stated before, IMC formation happens when the solder is in the molten state [30], but also during stressing of the solder joint with current. Even in a solid state some atoms are migrating to the IMC interfaces due to effects such as bulk diffusion. These atoms then react with the IMC, leading to a thickening of the IMC layer [2], [26], [31], [32]. Higher current stress and higher temperature can increase the diffusion processes, leading to more pronounced growth of these IMC layers [2], [11]. The Cu required for the reactions is supplied by Cu diffusion from the pads [10], [14]. The IMC conversion of the solder joint is a major problem, especially in smaller solder joints, like those used in 3D packaging of Si chips, where a solder joint may be in the 100 μm scale. Chen et al. [11] have shown that very small scale (30 μm) BGA solder joints could be completely converted into IMC. Other studies have shown that the IMC growth process could be enhanced by both thermal and electrical [33] effects. In some studies, where high current is applied, but no active cooling is used, the thermal effects cannot be avoided and are not easily distinguished. Abdulhamid et al. [26] reasons that thermomigration happens by Cu dissolution from anode and IMC growth at cathode in their study, while electromigration happens in the opposite direction, therefore the two effects should be opposing. This however is only applicable to specific test vehicles, where during the test the anode will be higher in temperature than the cathode.

2.2.1 Black's equation

Electromigration induced failure mechanisms have been studied for decades. SAC solders are more brittle than their Pb counterparts and are more prone to mechanical failures [2], [4], [14], [32]. Black [34] has produced a theoretical model for estimation of failure times for electromigration induced cracking. The model is as follows:

$$\frac{1}{MTTF} = AJ^2 \exp\left\{-\frac{\Phi}{kT}\right\}$$

Equation 2-6 – Black's equation [34]

Where $MTTF$ is the median time to failure in hours, A is a constant containing a factor for the cross-sectional area of the film, J is the current density in A/cm², Φ is the activation energy in electron volts, k is Boltzman's constant, and T is the temperature in K. While Black's equation was developed for Al thin films, it is used today in the estimation of failure time for PCB solder joints [1], [33], [35]. The equation is used both in its original form [35] and in some cases in a modified version to produce better agreement with recent findings, such as [33]:

$$MTTF = A \frac{1}{(cj)^n} \exp \left\{ \frac{Q}{K(T + \Delta T)} \right\}$$

Equation 2-7 – Modified Black's equation [33]

Where A is the constant cross-sectional area of the joint, c represents constant current crowding, j is current density, n is a model parameter for current density, Q is activation energy, k is Boltzman's constant, T is the solder joint temperature in K, and ΔT is the increase in temperature due to Joule heating.

2.3 Thermomigration and electromigration in solder joints

When current stressing the solder joint, Joule-heat is generated in the solder matrix. The Joule-heat generated as such can be described as:

$$\frac{dP}{dV} = \mathbf{J} \cdot \mathbf{E} = J^2 \rho$$

Equation 2-8 – Joule-heat in differential form

Where dP/dV is the power generated per unit volume, $\mathbf{J}$ is the current density vector, $\mathbf{E}$ is the electric field vector, J is the absolute value of the current density vector, ρ is the resistivity of the conducting material. Clearly, dP/dV will increase with an increase in current density, leading to more heat being generated in the conducting medium.

The Joule heat will therefore cause an increase in solder joint temperature. Some works have shown, that when the test vehicle is ~70-80 °C, temperature inside the joint could be significantly higher [19]. This is an even bigger problem, when instead of the solder joints' it is the ambient air temperature that is monitored, and the temperature difference could be even greater. The effect is also enhanced by current crowding. Straubinger et al. [2], [31] have shown that if the PCB track is coming in at angles from 45° or 135° angles (see Figure 3-2 in Section 3.2), the current density could significantly increase in the corners compared to the rest of the joint. Without active cooling, current crowding such as this could create localized hot spots,

where temperatures may be high enough to momentarily melt the solder [7], [9]. Since electromigration effects are faster in the molten state, since atoms require less energy to be contributed for transport. In the molten state chemical reactions and process also may play a part [9], thus the hot spot creation could exacerbate the electromigration. During current stress tests, this melting phenomenon should be avoided, since in these tests the current is usually increased compared to the application, in my case, 4 A current is rarely applied to 0402 and 0603 resistors in the field. There are also diffusion processes happening in the solder joint due to thermal gradient, which could produce effects like that of electromigration [12], [19], [26]. Thermomigration happens from the hot side of the joint to the cold side of the joint [12], which could both enhance or inhibit the electromigration phenomena. To avoid thermally induced or enhanced migration effects, active cooling should be used during current stress test, where the focus of the study is electromigration. In literature, several techniques are used, such as putting the test vehicles into climate chambers [19], immersion in liquid coolant [9]. In my case, air cooling was used and is assumed to be sufficient to keep the solder joint temperature under the melting point of the SAC305 (Sn 96,5 %, Ag 3 %, Cu 0,5 %), which is above 200 °C, and low enough so that thermomigration is negligible.

Electromigration and thermomigration phenomena may sometimes be difficult to differentiate. While some studies, like [26] suggest that the two processes have opposing polarities, and therefore can be differentiated, other studies, such as [12], [19], [36] suggest that thermomigration phenomena can have the same polarity effect as that of electromigration, resulting in enhanced material transport. It is also shown that heating due to current stress may lessen the energy required for atoms to be moved out of the structure, resulting in increased electromigration if the test vehicle temperature is not controlled properly [9], [18]. Measuring said temperature is also not trivial, as it was shown in [19] that when monitoring the temperature on the backside of the test vehicle (opposing the solder joint), even though the test vehicle itself has only reached 125 °C, the solder joint had already melted locally, indicating a temperature difference of >50 °C. Ref. [37] comes to similar results using simulation.

In [1] the authors have created a system where it is possible to continuously monitor the cross sections of the samples using microscopic imaging during electromigration tests, supplying data about the process. They have shown that current stress may lead to failure by cracking of the joint and that the crack is not necessarily at the peak current density point, because the electromigration and current stress can create mechanical stresses elsewhere in the joint and

cracking will happen at the point where stress is maximal. Relaxation due to recrystallization may also start in this point [22], [38].

Refs [11], [12], [35], [36], [37] have investigated electromigration effects in very small-scale solder balls ($\sim 10\text{-}100\text{ }\mu\text{m}$), like those used in chip-scale packaging. These solder joints show even larger effects of current induced electromigration. It was even shown in [11] that current stress may be used to convert the whole solder ball to IMC. Ref. [39] has shown that the UBM (Under Bump Metallization) has a big influence on electromigration, for example, Fe-Ni UBM behaves significantly better than Cu UBM, with SAC solder.

2.4 Evolution of IMC layers during electromigration

As stated before, the IMC layer thickness and structure may change during electromigration phenomena both in terms of thickness and in terms of morphology. There are numerous studies discussing the evolution of IMC layers in the literature [2], [11], [14]. The initial IMC layer grown during the reflow process tends to be a scallop-type structure [40], meaning it is formed out of larger grains connected loosely, however, after current stressing, the IMC layer structure may go through a refinement and thickening, resulting in smaller, more closely packed grains [14]. Figure 2-4 demonstrates the evolution of IMC layer after current stressing.

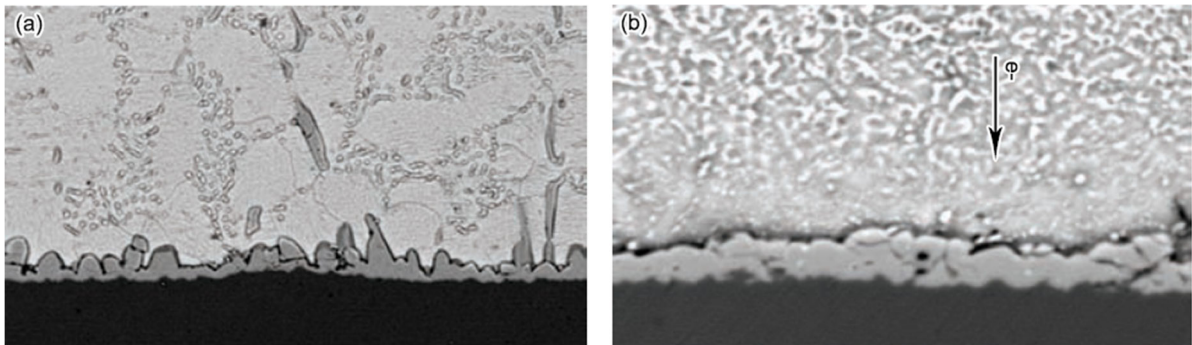


Figure 2-4 – IMC layer evolution in literature. Left (a): scallop-type, as-reflowed IMC, right (b): refined, planar IMC structure [14].

2.5 NP doping of solder joints

The doping of solder joints with nanoparticles to improve IMC growth and EM (electromigration) behaviour of the joints has been investigated in many works [6], [15], [16], [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53]. The effect of nanoparticle doping on IMC growth at cathode in as-reflowed state and after 1128 h current stress at $1 \cdot 10^4\text{ A/cm}^2$ is shown in Figure 2-5 and Figure 2-6. The ability of Ni NPs to suppress electromigration damage in the solder joint is clearly visible.

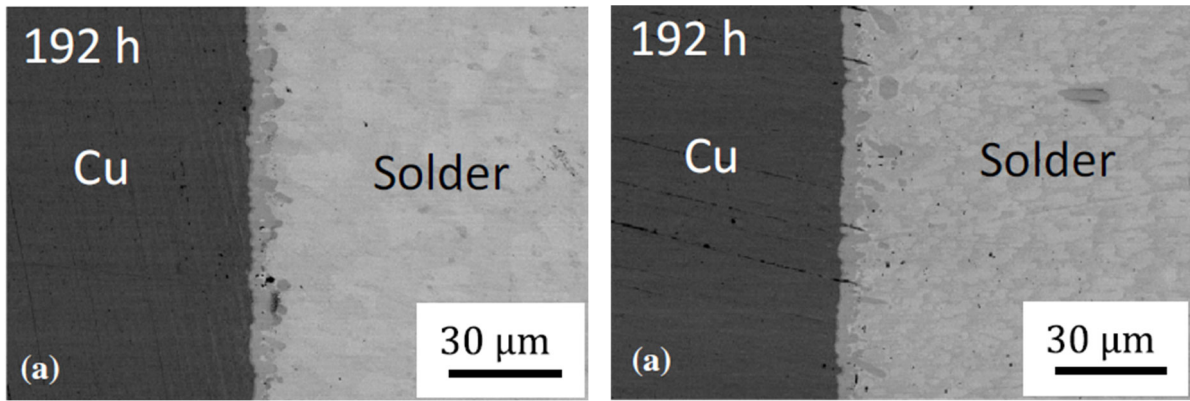


Figure 2-5 – Comparison of IMC growth of undoped solder joint and doped solder joint in as-reflowed state. Left: undoped, right: 2 wt. % Ni NP doped [51].

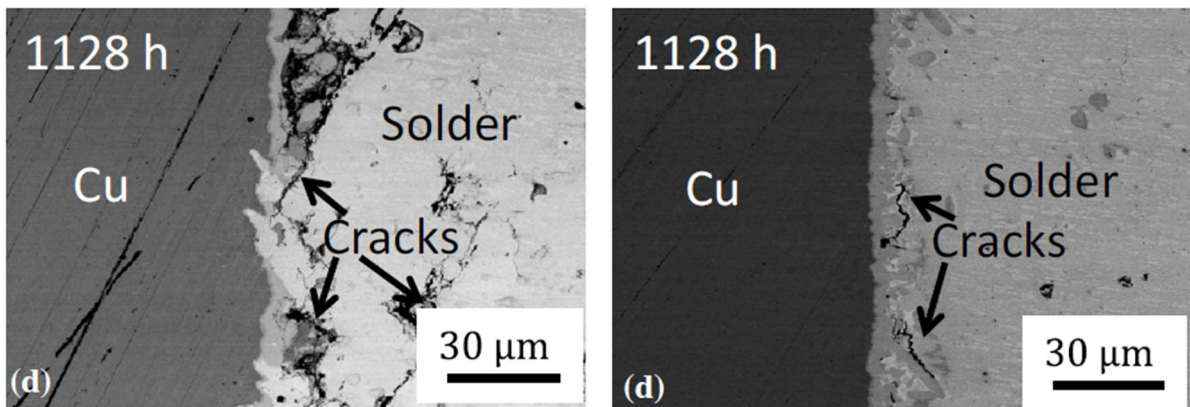


Figure 2-6 – Comparison of IMC growth of undoped solder joint and doped solder joint after 1128 h current stress. Left: undoped, right: 2 wt. % Ni NP doped [51].

In [15], the authors have investigated the ability of NP addition, to limit the IMC growth during the initial soldering phase, by adding Cu nanoparticles to pure Sn solder balls. The nanoparticles reduce the Cu_5Sn_3 and Cu_3Sn IMC growth during the soldering process, however, in this study, the behaviour of the solder in the solid state was not investigated further. The change in the IMC layer is visible in Figure 2-7. The authors theorized that the metallic NPs work as nucleation sites, producing denser but thinner IMC layers. Ref. [41] has shown that the addition of Zn NPs to the solder material decreases IMC growth both in the liquid and the solid state. They have also found that 3 wt. % Zn addition inhibits IMC growth almost completely for CoSn_3 IMC. The ability of metallic NPs to improve the wetting properties of solder, IMC growth reduction and shear strength improvement was shown in [42] by Ni NP addition. Other works have also explored the application of various metallic NPs to the solder, finding similar results [46], [47], [48], [49], [51], [52], [53].

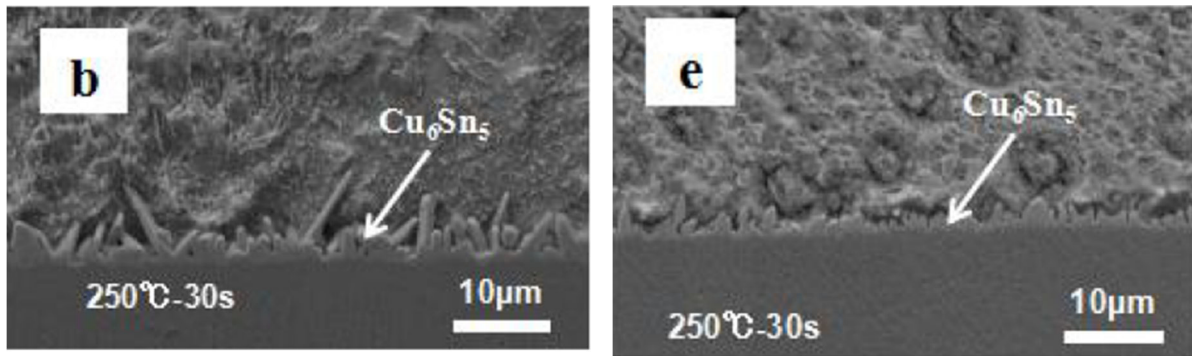


Figure 2-7 – Comparison of undoped and doped solder IMC layer after reflow. Left: undoped, right: 0.2 wt. % Cu [15]

Besides metallic nanoparticles, ceramic particles have also been used in literature [6], [43], [45], alongside intermetallic NPs [16], [44]. In [45] the authors have shown that the addition of TiO_2 NPs increases the thermal shock resistance, decreases the IMC growth rate, and increases the shear strength of the joint. The addition of the TiO_2 nanoparticles also changes the microstructure of the IMC to a finer structure. Similar morphological changes were observed for example in [16], [42], [44]. The authors have investigated the addition of Cu_6Sn_5 nanoparticles to the flux in [44] and directly to the solder paste in [16], both finding improvement in the behaviour of the solder for IMC growth and EM damage (see Figure 2-4, Figure 2-5, Figure 2-6 and Figure 2-7).

Lastly, some of the studies have dealt with the addition of heavy metals to the solder material [46], [49], [50]. The authors of [46] have found that the addition of Sb (antimony), which is a heavy metal causes the development of finer microstructure and IMC reduction. In [48] an experiment was developed where multiple NPs (Ni and Fe) were used at the same time at low concentrations < 1 wt. %, resulting in improved IMC layer thickness, but Ni and Fe by themselves also reduced the thickness of Cu_3Sn significantly. The authors of [49] theorize that a small addition of Fe can create a thin layer of FeSn_2 on the IMC layer, inhibiting diffusion, but will not grow significantly when aged, resulting in less EM behaviour of doped samples.

Many of the studies show that the addition of NPs to the solder may reduce IMC thickness, for example: [6], [15], [16], [41], [44]. The explanation for this behaviour is that the NPs sit on the IMC layer, blocking diffusion paths, similar to the explanation for Fe before. The smaller rate of diffusion will result in a limited IMC growth. At higher concentrations, agglomeration has been observed with worse IMC growth inhibiting properties [42], [47], [50]. The studies also agree, that the addition of NPs can produce finer microstructure of the joint, resulting in higher mechanical strength [42], [45], [50], [52]. Lastly, the NPs are often introduced to the solder joint in the flux, similar to this study [15], [44], [51].

3 Sample preparation

3.1 Nanoparticles and solder materials

To study the electromigration and IMC growth behaviour of chip-scale solder joints, 0 Ω SMD resistor were chosen in sizes 0402 and 0603. The resistors were prepared in groups of 15, in rows of five (see Figure 3-1). The PCB plans were prepared by Dániel Straubinger for a previous study [2]. The resistors on the PCBs were connected in series and the PCBs were connected in a daisy chain configuration. The PCBs were prepared from RO4000 ceramic material, due to the better thermal behaviour compared to FR-4 substrates. RO4000 which are made from a hydrocarbon ceramic have better heat conductivity and higher glass transition temperatures than their FR-4 counterparts, for reference, see example datasheets in [54], [55]. The better heat conductivity creates a more uniform heat distribution with the solder joints, making thermomigration effects negligible after analysing the temperature data.

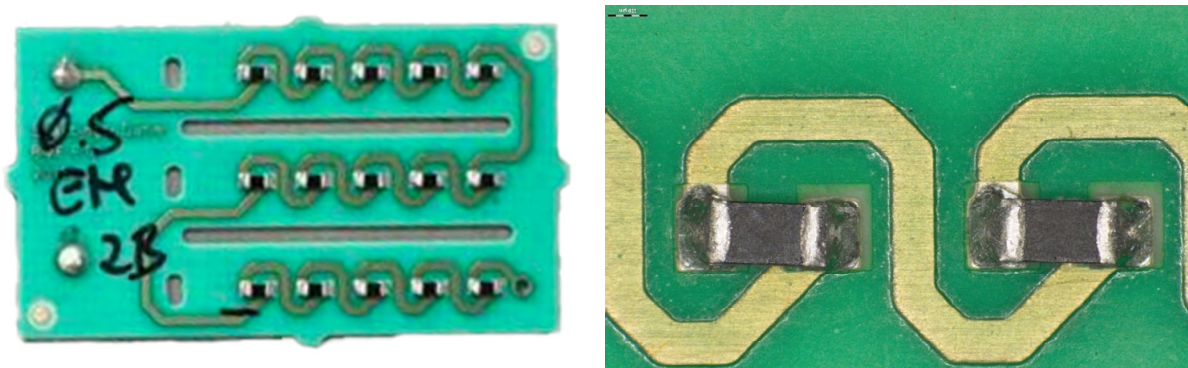


Figure 3-1 - Electromigration test vehicle. Left: bird's eye view, right: close-up of resistor

Fe nanoparticles (Nanografi) were acquired with a mean particle diameter of 40-60 nm and an oxide thickness of 5-6 nm, resulting in nanoparticles that are stable in air. The NPs were mixed with a commercial, no-clean, halogen free flux (TACFlux 089HF, Indium Corp) at different concentrations (0.5, 1 and 2 wt. %). Introducing the NPs to the solder joint in the flux is an established method [15], [44], [49], [51]. This method reduces the risk of NP agglomeration in the solder joint during soldering [56], [57]. The addition of NPs to the flux should provide a high concentration at the interface, but a low overall doping level. To provide a uniform NP distribution in the flux, and to remove agglomerates, blending was done in a centrifugal planetary mixer (THINKY ARE-250) at 2000 rpm for 2 min. The Fe doped solder paste was prepared by Irina Wodak, PhD student, from TU Wien, also the sample assembly and systemic grouping was overseen by her.

The resistors were soldered onto the PCB using SAC305 (Sn 96.5 %, Ag 3.0 %, Cu 0.5 %) solder balls, with respective diameters of 0.4 mm and 0.5 mm for the 0402 and 0603 resistors. The melting point of the SAC solder used in this study is 217 °C. The soldering was done in a VPS (Vapor Phase Soldering) chamber, using a ASSCON VP800 soldering system at 230 °C. During VPS, the heat is supplied to the PCB board using a material called Galden. The Galden is heated to its boiling point and forms a vapour around the board. The Galden in the air then condenses onto the PCB board, supplying the heat. Since condensation happens uniformly, VPS allows the whole board to be heated uniformly, while in an infrared soldering system, components with a higher absorption would be heated to a higher temperature while the board is being soldered. Therefore the VPS soldering allows better thermal control than many other soldering techniques [58]. The process ended with vacuum cooling to reduce the amount of gas voids and flux remaining inside the joint, producing joints with fewer voids.

3.2 Measurement setup overview

After soldering, the PCBs were mounted onto Al trays to provide heat spreading. Silicone TIM (thermal interface material, T-Global TECHNOLOGY) was applied between the PCBs and the heat spreaders to provide better thermal contact between the surfaces. The trays were placed into a chamber with ventilation to provide active cooling during the measurement. Active cooling is necessary to reduce the prevalence of Joule-heating, which could produce significant recrystallization and diffusion in the solder joint [3], [22], [24], and it would have been difficult to differentiate between thermal and electromigration effects after the measurement.

The power source for the measurement was a Xantrex XDC 60 industrial DC power source. The daisy chains were loaded with 4 A current for 1000 h, 2000 h and 4000 h. A schematic of the setup is visible in Figure 3-3. During the current stressing temperature was monitored using K-type thermocouples mounted onto the trays and PCB boards. The temperature was later monitored using BME280 and BME680 environmental sensors. The stressing setup was performed by me and my supervisor, the monitoring (setup and data acquisition) was performed by me. The current path in the sample is shown on Figure 3-2.

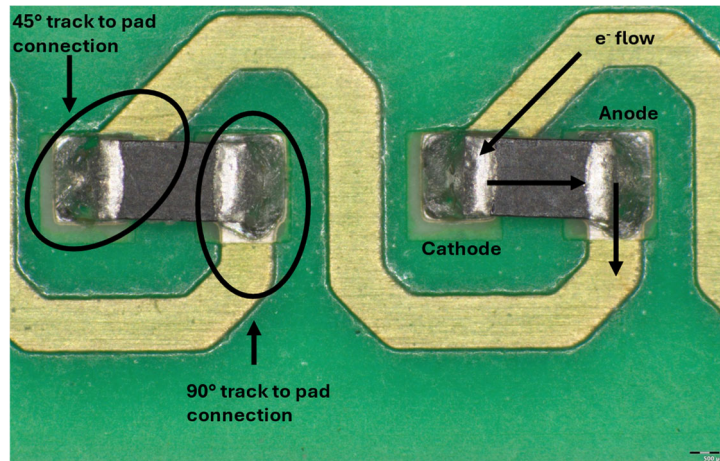


Figure 3-2 – Current path on test vehicle

A block diagram of the experimental setup can be seen on Figure 3-3. The samples were stored in a chamber, which was cooling its storage volume with active air ventilation, by removing the dissipated heat to the room environment. The chamber had an outlet on the backside to achieve air flow.

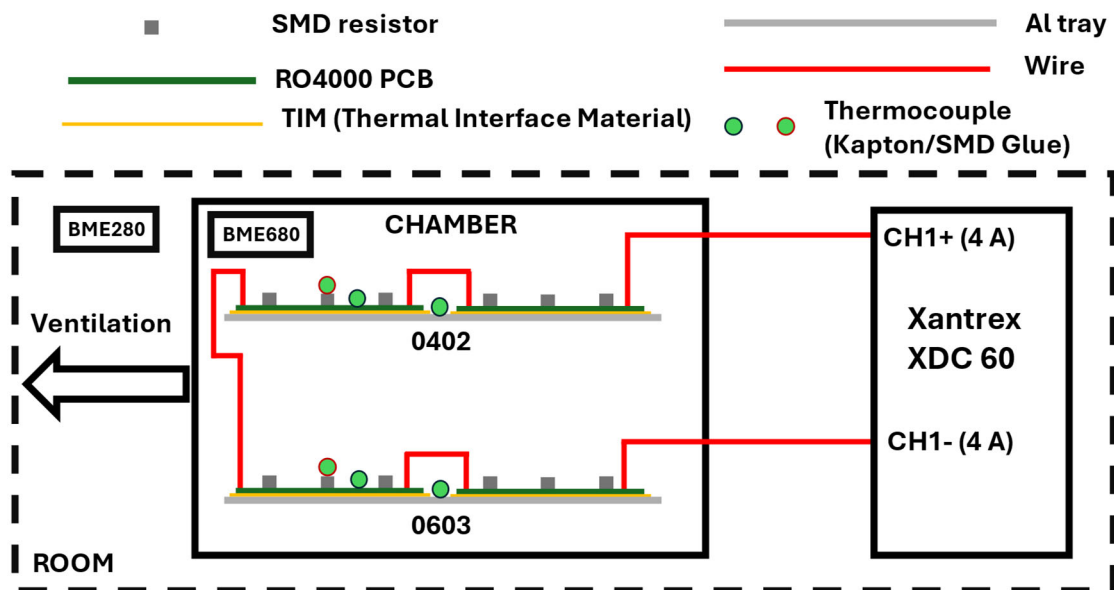


Figure 3-3 – Experiment setup

After stressing, the samples were examined using cross-sectional analysis (5 samples/board) and shear testing (Dage 2400 shear tester, 10 pcs/board). The cross-section preparation was performed by EFI-labs. The results and methodologies for these tests are discussed later.

3.3 Temperature measurement

The block diagram of the temperature measurement can be seen on Figure 3-4. The temperature was initially monitored using K-type thermocouples connected to Novus MyPCLab data loggers. The data loggers were connected to the PC using USB cables. The following temperatures were recorded with the thermocouples: top tray, bottom tray, 0603 PCB temperature with SMD glue, 0402 PCB temperature with SMD glue, 0603 resistor temperature with Kapton tape, 0402 resistor temperature with Kapton tape (Figure 3-3). After the initial temperature step was recorded, the MyPCLab loggers were removed to be used elsewhere, and temperature monitoring was continued using an Arduino UNO R4 Wi-Fi controller and BME280 and BME680 sensors.

The setup for the Arduino is shown in Figure 3-5. The BME sensors were both connected to the Arduino board over I²C interface. The BME280 sensor was used to monitor the air parameters (temperature, pressure, humidity) of the room while the BME680 sensor was used to monitor the air parameters inside the test chamber. After taking a measurement, the Arduino idled for ~1 min. This sampling frequency, based on the data from the thermocouples (Figure 3-6) is enough to record the thermal transients but avoids creating large files. The Arduino sent the data over a COM port to the computer, where a CoolTerm serial monitor was used to save the data to a .txt file. The data was later post-processed using Python, with pandas and matplotlib library packages. The recorded temperature data is shown in Figure 3-7, while for the sake of brevity the pressure and humidity data are not discussed here.

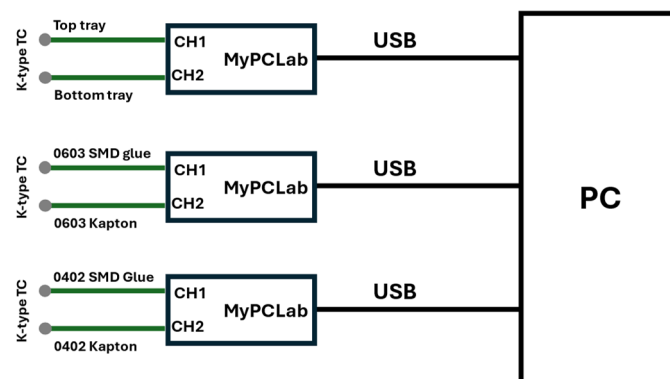


Figure 3-4 – Temperature measurement block diagrams of thermocouples and MyPCLab loggers

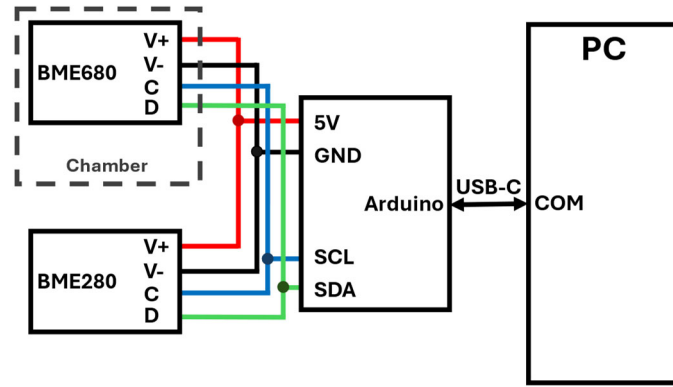


Figure 3-5 – Temperature measurement block diagram of Arduino and environmental sensors

The initial thermal response of the system during the measurement is shown in Figure 3-6. The temperature of the boards was measured using the thermocouples for 4 h after turn-on. The 0402 resistors reached $\sim 80^{\circ}\text{C}$, the PCBs $\sim 72^{\circ}\text{C}$ and the 0603 resistors reached $\sim 78^{\circ}\text{C}$ and the PCBs $\sim 70^{\circ}\text{C}$ temperatures. The temperature in the chamber was later monitored using an Arduino board and BME280 and BME680 environmental sensors. A section of the data from the measurements of the environmental sensors is visible on Figure 3-7. The figure shows that the temperature inside was stably $\sim 5^{\circ}\text{C}$ above the temperature of the room the chamber was in. The drop in the temperature at the end is when the test vehicles for 2000 h were removed from the chamber and the whole setup was powered down, so the temperature could equalize with the room. The temperature and pressure recorded will be later used for finite-element modelling of the temperature chamber.

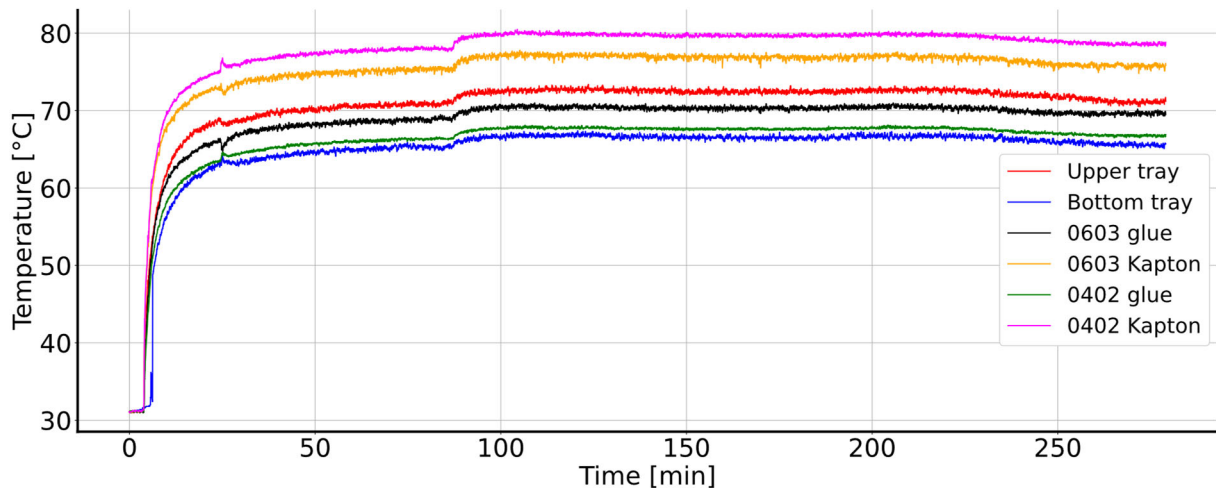


Figure 3-6 – Thermal response of PCBs at turn-on

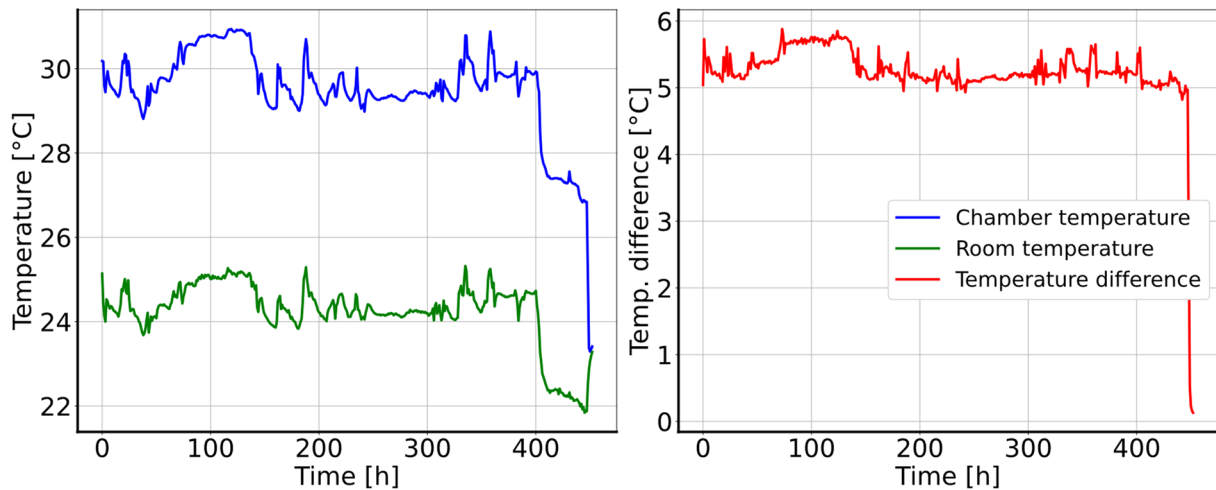


Figure 3-7 – Chamber temperature vs. room temperature

3.4 Needle-like IMC structures on surface of 0402 solder joints

The 0402 samples showed needle-like IMC structures (Figure 3-8 and Figure 3-9) on the surface of the solder joints. While there is literature showing that the recrystallization of the solder joint is possible due to electro-thermal loading, the resulting structures are different from those that can be observed in the pictures. However, in [59] the authors have shown that the rapid cooling after the reflow procedure may create these tree-like structures of IMC in the solder, the structures from the literature are shown on Figure 3-10. The close resemblance of the IMC structure between Figure 3-9 and Figure 3-10 is clearly visible. Since the soldering was done in a VPS system with vacuum cooling, it is possible that the cooling rate was sufficiently low to produce the effect from [59]. This however causes no further problems in the investigated phenomena.

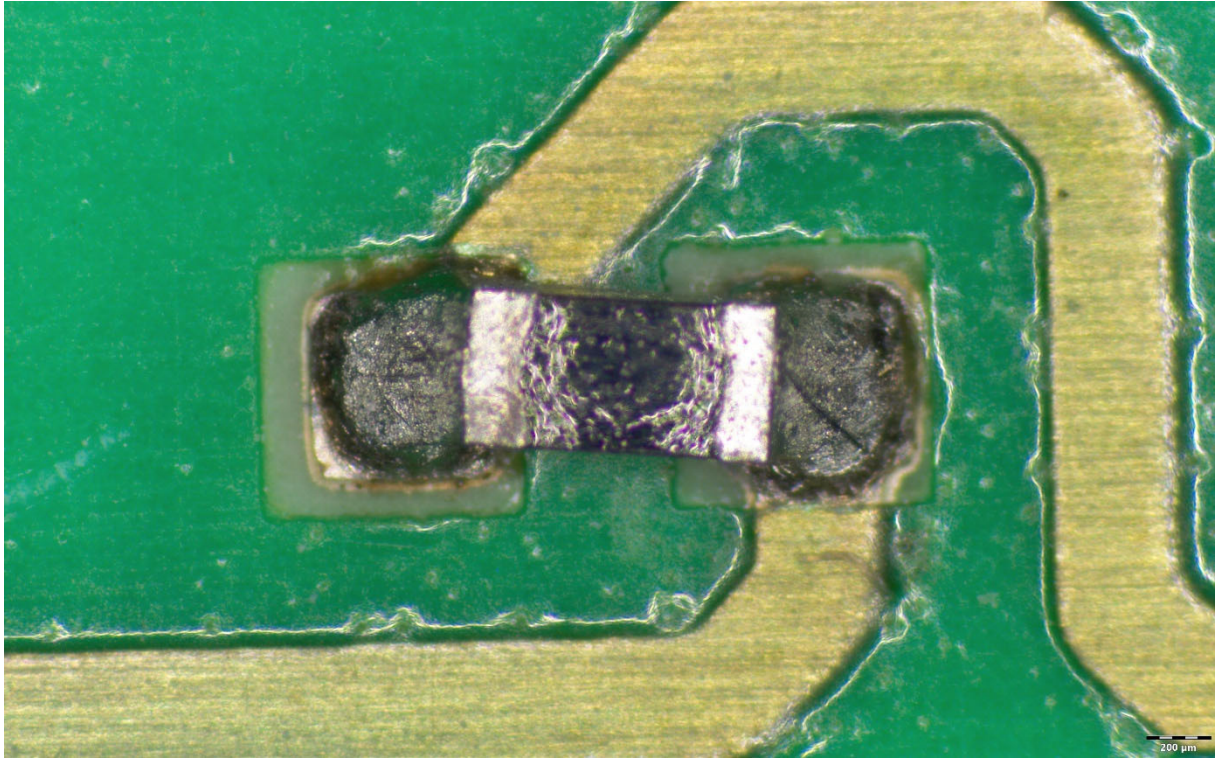


Figure 3-8 – Surface of as-reflowed sample showing needle-like IMC structures

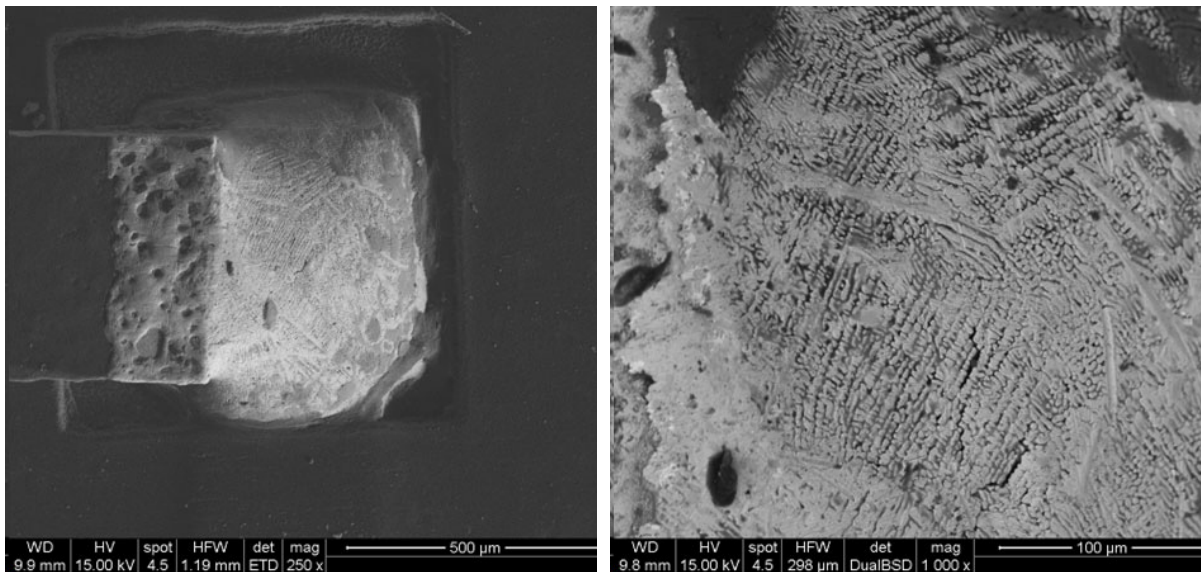


Figure 3-9 – SEM image of sample showing need-like IMC structures. Left: bird's eye view, right: close-up of surface

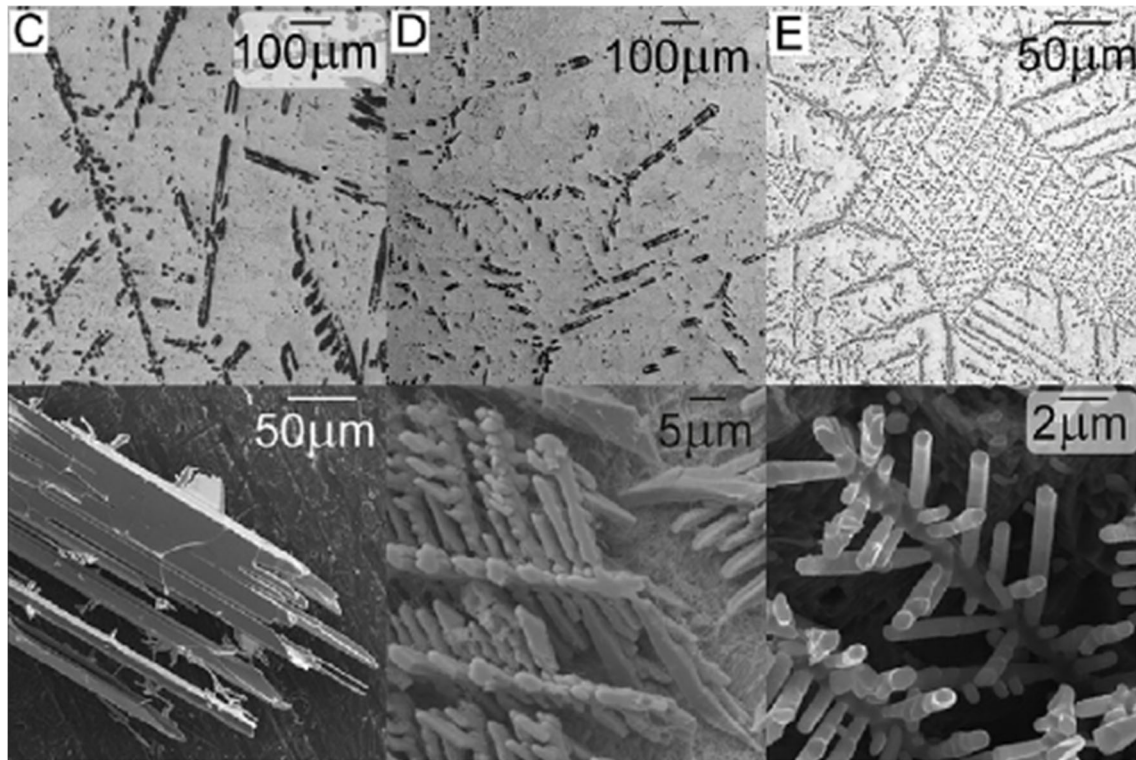


Figure 3-10 – IMC structure created by rapid cooling [59]

There was also Pb found in the solder matrix. After examination of the materials used it was determined that the Pb was found in the protective layer of the SMD resistors and was possibly removed and transported to the solder cross-sections during the grinding and polishing process.

4 Results

Due to the low number of samples being tested, statistical methods and numbers such as standard deviation are not appropriate (sample number < 10). Because of this, the results of the tests are visualized on bar charts and the error bars show the minimum and maximum values of the data.

4.1 Electromigration effects in doped and undoped solder joints

Some of the samples were examined using cross-sectional analysis (5 pcs/board). Cross-sectional analysis was done using an Olympus optical microscope and Quanta 200 scanning electron microscope (SEM). The samples were examined at 1000 h, 2000 h and 4000 h of testing. Straubinger et al. [8] have shown previously that the highest current density point in the solder joints can be expected at a track connection angle of 45° and 135°C (see Figure 3-2 at Section 3.2). The samples were cut, ground and polished to investigate the part of the solder joint where the highest current density would be expected. Figure 4-1 shows the cross-section of two as-reflowed samples, on the left, an undoped and on the right a sample with 0,5 wt. % doping. No significant microstructural difference can be seen in the images.

The samples at 1000 h showed no definite, visible microstructural changes compared to the as-reflowed state. This was true both for 0402 and 0603 components. 0603 components showed no significant microstructural change due to electromigration even after significant current stressing (4000 h).

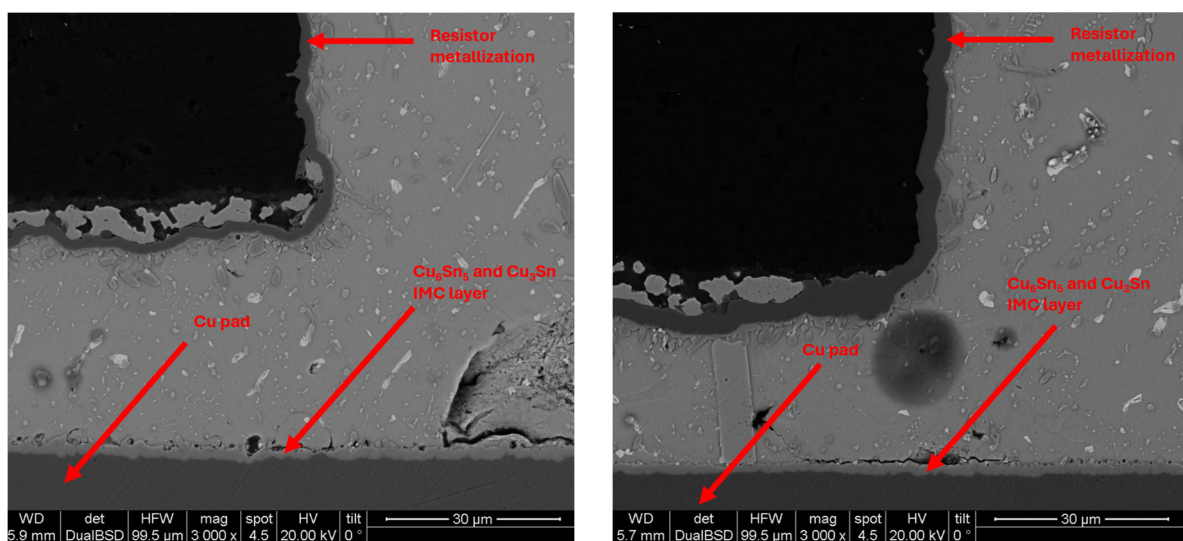


Figure 4-1 – Cross-section of sample in the as-reflowed state. Left: 0 wt. %, right: 0,5 wt. % doping.

After longer current stress the 0402 samples began showing signs of electromigration. Figure 4-2 shows the current path in the sample. Electrons enter at 135 °C connection at the cathode, resulting in significant current crowding according to Straubinger et al. [2], [8]. The electrons then go through the device and exits on the anode side, at a 90° track-to-pad connection. The connection angle is lower here; therefore, the current density should also be lower in the anode side solder joint compared to the cathode side joint. Due to this effect, electromigration is mostly expected on the cathode side of the component. The crowding of the current on the cathode side increases the probability of electromigration effects. This results in the dissolution of the Cu pad into the solder matrix, and the thickening of the IMC layer.

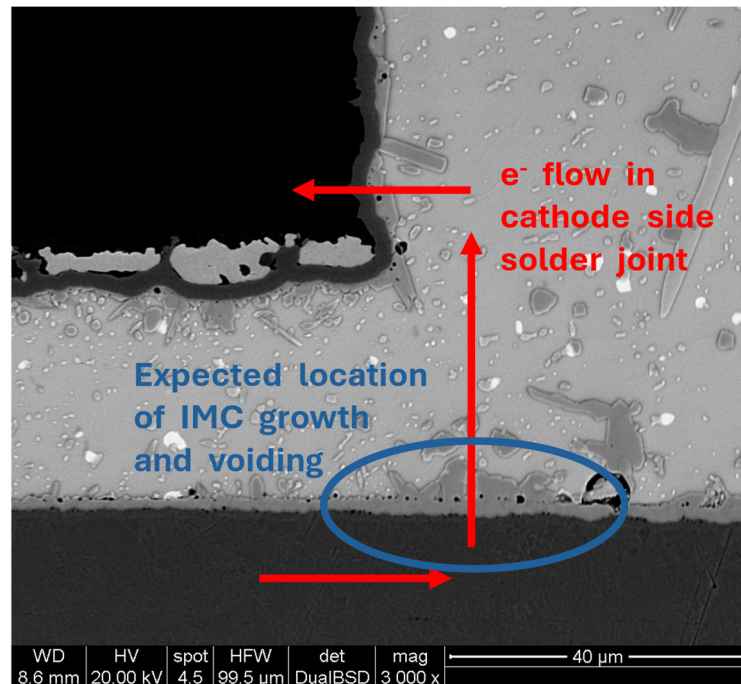


Figure 4-2 – Current path at cathode of resistor

Figure 4-3 shows the evolution of the Cu pad-solder joint interface. The dissolution of the Cu at the cathode side of the joint can be seen in a cavity-like fashion. This kind of dissolution can be attributed to electromigration phenomena according to literature [9], [10]. Thermomigration phenomena causes IMC thickening of the joint, but not cavity-like Cu dissolution and voiding. Increased amounts of Cu₆Sn₅ or Cu₃Sn IMC were not found in the solder matrix. The samples prepared with 0.5 wt. % Fe NPs showed no Cu dissolution, even after 4000 h of current stressing. The samples with 1 wt. % and 2 wt. % Fe content showed Cu dissolution after 4000 h, but not after 2000 h of stressing. A possible explanation for this sensitivity to doping level is that at low doping levels, the Fe nanoparticles segregate in front of the Cu₆Sn₅ layer, forming FeSn₂, and blocking diffusion paths for the Cu particles by creating a uniform layer, while for higher concentrations, the NPs could agglomerate, resulting in an unevenly

distributed layer and allowing the diffusion of Cu atoms, although at a lower rate than in the case of undoped samples. The refs [42], [45], [47] corroborate this idea.

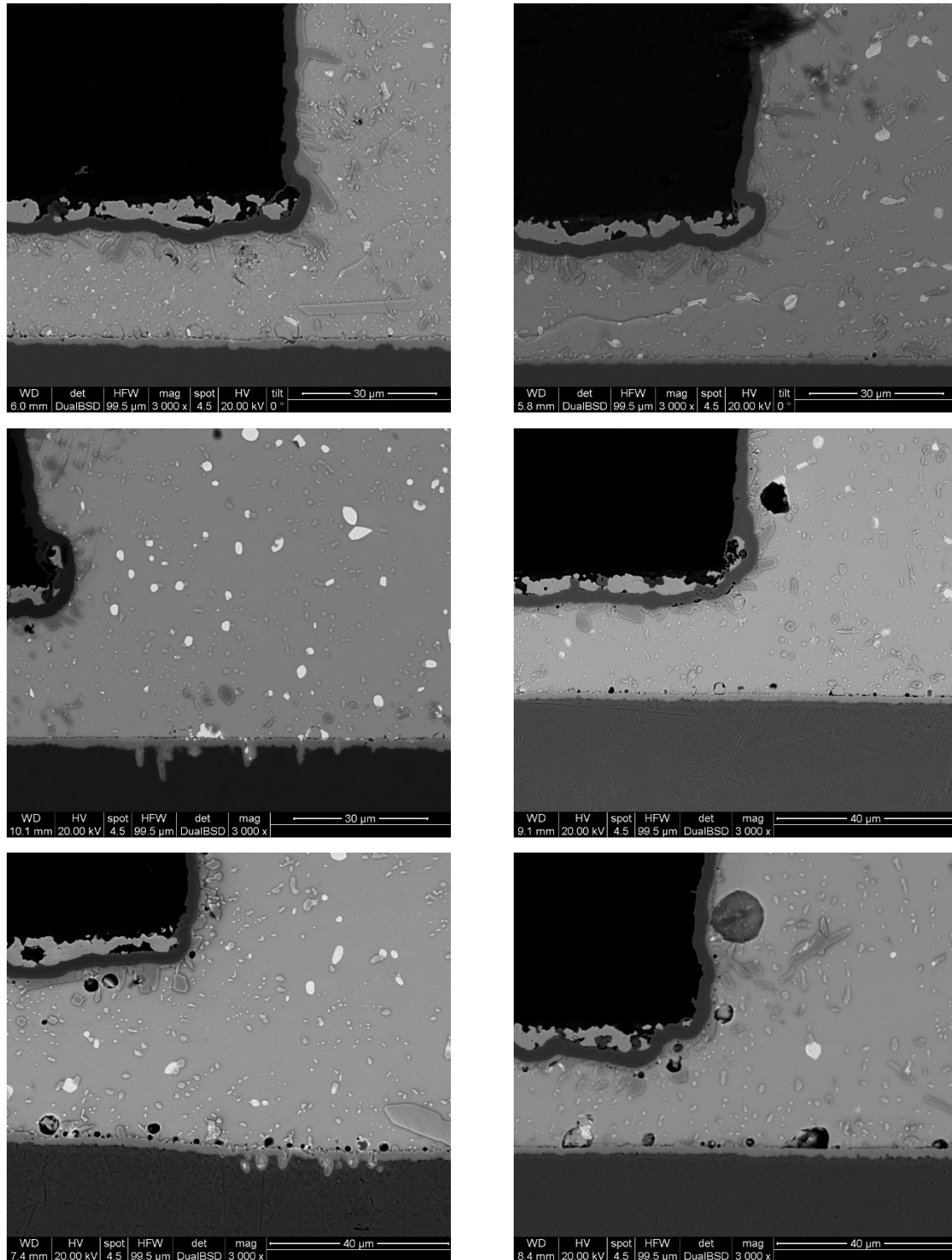


Figure 4-3 – Evolution of Cu-SAC interface of 0402 resistor. From top to bottom: 0 h, 2000 h, 4000 h current stress. Left: 0 wt. % doping level, right: 0,5 wt. % doping level.

0603 resistors showed no Cu dissolution. This is probably since the increased cross-section reduces the current density, even in the hot spot where current crowding would be expected to create a higher density. Literature have shown that for EM damage to occur in the Cu pad, a critical current density must be reached, and if the current density is lower than the critical value, electromigration induced voiding and Cu dissolution will not occur [9], [60]. Since the soldering surface of a 0603 resistor is approx. 2,19x larger than that of the 0402, the current densities could be significantly lower.

4.2 Shear strength evolution

The shear strength of the joints was examined using a Dage 2400 shear tester at a shearing speed of 200 μm per second on 10 resistors per PCB, the actual measurements were performed by Irina Wodak. The shear strength of both the 0402 and 0603 resistors was investigated. The results of the shear strength between the reference (0 h loading) and the loaded samples is shown in Figure 4-4 for 0402 samples and Figure 4-5 for 0603 samples.

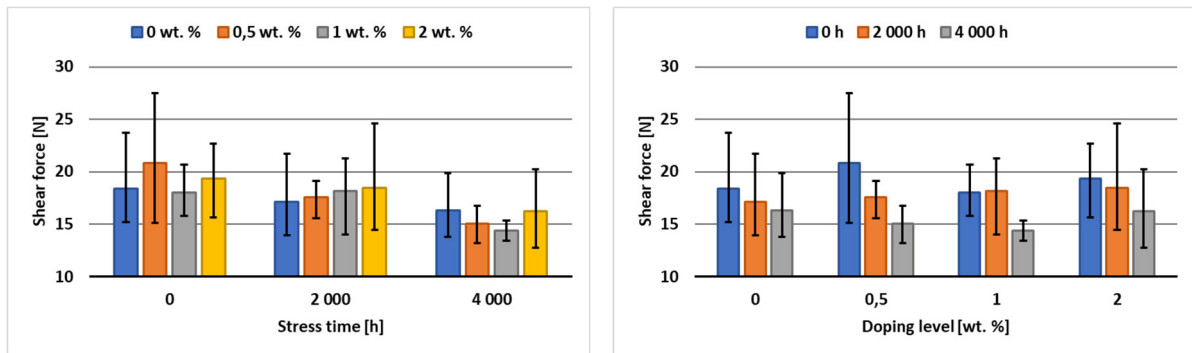


Figure 4-4 – Shear strength of 0402 samples

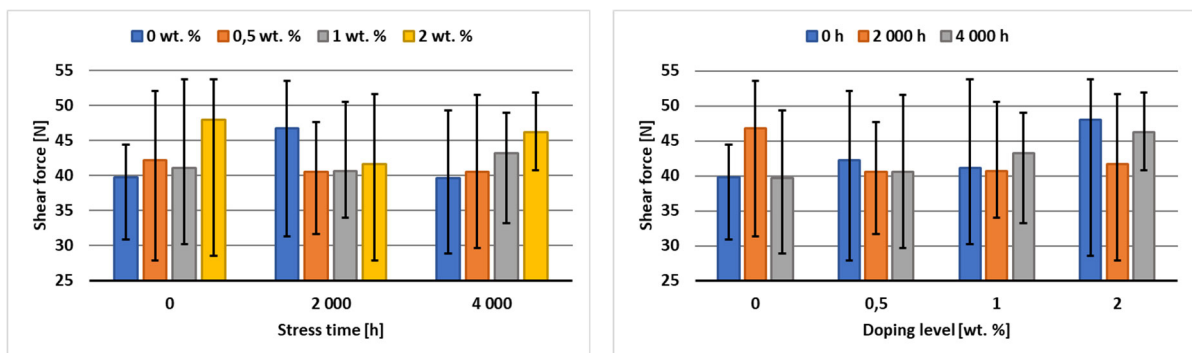


Figure 4-5 – Shear strength of 0603 samples

The assumption was made initially, that the shear strength from Cu adhesion for the components is in the same order of magnitude for 0402 and 0603. Due to this, some of the components failed due to pad lifting. The result from those components is omitted from the analysis. It can be seen in the figures above (Figure 4-4, Figure 4-5), that the shear strength of

the 0402 resistors was higher in cases of 0.5 wt. % and 2 wt. % doping, while it was slightly lower for 1 wt. % doping, but the samples with doping performed at least as well as the reference samples. After stressing the resistors for 4000 h, the 0402 resistors showed significantly decreased shear strength across the board. The source of this decrease could be the combined electrical and thermal stress of the joint, and damage due to current crowding (see Section 4.4). The thickening of the IMC layer could be one of the possible explanations, as the IMC is generally more brittle, however, the evolution of the IMC layer will be discussed in the following section. An important thing to note is that in the case of 0402 resistors, the range of the shear strength after 2000 h and 4000 h was smaller for doping levels of 0.5 wt. % and 1 wt. %. It is documented in literature that higher levels of doping may cause the agglomeration of the NPs, and it could be the case that for these doping levels that NPs are dispersed such that they produce a more uniform solder joint structure. On the left diagram, the shear strength decreased for all samples after loading, regardless of doping level, however the doped samples show better performance than the undoped samples at 0 h and 2000 h load.

For the 0603 resistors, all doping levels showed higher initial shear strength than undoped samples. 0603 resistors did not show change in the shear strength after current stressing for 4000 h. This could be because the thermal stress and the stress from the current density are both slightly lower for the 0603 resistors than for the 0402 resistors. The joints doped with 2 wt. % showed better higher shear strength both before current stressing and after 4000 h of stressing. It should be noted that the undoped 0603 samples tested after 2000 h load showed very high shear strength, however this might be a selection anomaly, where a few outlier samples were accidentally selected. Based on the data at 0 h and 4000 h this kind of result would be unlikely to occur if the number of samples was higher.

4.3 IMC growth behaviour

4.3.1 IMC thickness measurement method

I measured the IMC layer thicknesses; the measurements were done on SEM images taken at 3000x magnification at TU Wien. The Magic Wand tool was used with a tolerance level <10 to select the IMC layer based on pixel colour. After selection, the number of selected pixels was divided by the width of the image (1024 px) which resulted in the average thickness of the IMC layer in pixels. This value was then multiplied by length represented by a single pixel, calculated from the number of pixels in the size line on the pictures. An example calculation is shown in Equation 4-1. Where P is the total number of pixels in the IMC layer, w is

the width of the image in pixels, W_{px} is the width of the size line in pixels, $W_{\mu m}$ is the size line in μm , x is the average thickness of the IMC layer in μm .

$$x = \frac{PW_{\mu m}}{wW_{px}}$$

Equation 4-1 – Calculation method for IMC thickness in SEM cross-sectional images

AI based tools were also investigated for their applicability for the task (images segmentation based on colour), however they either provided inaccurate results, or were difficult to use. Their practical setup and the teaching of the system would require efforts which were not available in the framework of this current research. One candidate would be CVAT.ai [61] which was highly accurate and easy to use, however for the segmentation of ~ 100 images, a paywall was reached. This means that currently Photoshop or similar bitmap-based tools are still the best for this kind of task and number of samples. Since on the SEM images, the Cu_6Sn_5 and Cu_3Sn IMCs are not distinguishable, the measurement was done on the whole IMC layer.

4.3.2 Overall IMC growth

Hereby I discuss the IMC layer growth, which was only evaluated for 0402 samples at the time of writing this manuscript. The IMC layer growth of the 0402 samples is shown in Figure 4-6. On the cathode side of the resistors, the IMC layer growth from EM is expected to be in a very small volume of the solder joint. Because of this, the range of the IMC thickness measurement can be quite large, as the measured thickness depends largely on how accurate the cross-section polishing was in terms of finding the location of the EM phenomena (the point with maximum current density).

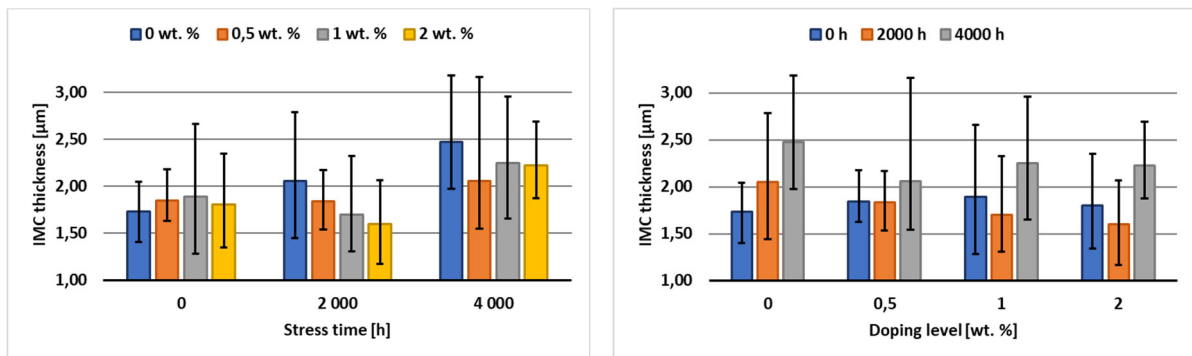


Figure 4-6 – IMC growth in 0402 samples

In Figure 4-6 the IMC layer thickness is calculated as the average of the measurements both at the anode and cathode of the resistors. It can be seen in the figures that the initial IMC thickness is slightly higher for the doped samples than for the undoped samples, however after

aging, the IMC growth is significantly lower for the doped samples than for the undoped samples. Although 1 and 2 wt. % doping initially suppresses the IMC growth in the solder joint better than 0,5 wt. %, after 4000 h current stress, the growth of the IMC is much higher. The best performance over the whole stress time is reached at 0,5 wt. % doping. The reason for the suppression of the IMC formation could be the following. During the reflow process, the Fe NPs are distributed uniformly at interface due to the flux doping. During the soldering process, the Fe NPs sit on the Cu_6Sn_5 and Cu_3Sn layer, or form FeSn_2 IMC [49], blocking diffusion paths for the Cu and Sn atoms, limiting the IMC growth process. At 0,5 wt. % concentration, the NPs are distributed evenly. For higher doping concentrations, the distribution of the NPs is possibly uneven due to agglomeration, resulting in a less uniform blocking of the diffusion paths to the IMC layer [42], [45], [47], [50]. The right side of Figure 4-6 shows that the IMC thickness increases in all samples after aging, regardless of doping, although to a smaller extent for doped samples. A comparison of the anode and cathode side solder joint IMC growth can be seen in the following section.

4.3.3 Comparison of IMC thickness at anode and cathode side

The comparison of the IMC thickness at the anode and cathode side of the resistors is visible in Figure 4-7. The diagram on the left shows the IMC layer thickness of the as-reflowed samples, and the diagram on the right shows the IMC layer thickness of the 4000 h stress samples. The diagrams show that the initial thickness of the IMC layer was in a similar range, between 1,5 and 2 μm . The diagram on the right shows that after current stressing of the samples, the IMC layer thickens on both the anode of the resistor and on the cathode of the resistor. On the anode side the undoped samples show significantly higher IMC growth, which would also be expected behaviour according to the literature [14], [33]. The cathode side also shows some thickening, although to a lesser extent. It is again visible here, that the 0,5 wt. % doped samples performed best, which is expected, since the Cu dissolution phenomenon, which would move Cu atoms into the IMC layer, was suppressed in the 0,5 wt. % samples, while the 1 wt. % and 2 wt. % samples began showing signs of Cu dissolution after 4000 h testing.

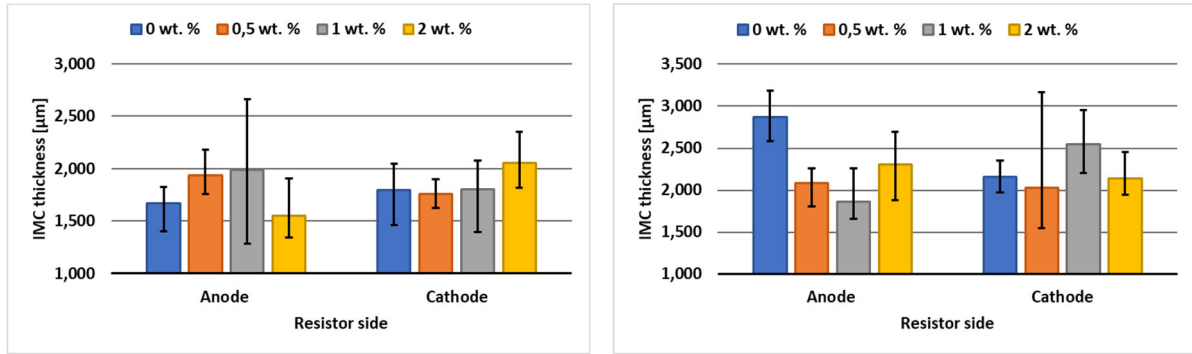


Figure 4-7 – IMC thickness of samples at anode and cathode. Left: as-reflowed, right: 4000 h current load

The IMC growth according to resistor contact (anode or cathode) is shown for 2000 and 4000 h load on Figure 4-8. We can see that the IMC growth happens on both sides of the resistors, but it is more prominent on the anode side, which is what is noted in literature. The ability of the Fe nanoparticles to suppress the IMC growth is clearly shown on both diagrams in Figure 4-8, but the effect is more visible on the anode side, where the higher growth would be expected. Here we can see that all doping levels reduce the IMC growth, but 0,5 wt. % and 1 wt. % are more effective at suppressing the IMC growth than 2 wt. % doping. On the cathode side, the 0,5 wt. % doping seems to be the most effective. The most probable reason for this is that the Cu dissolution on the cathode side is suppressed completely at 0,5 wt. % doping level, which could lead to reduced IMC growth compared to 1 and 2 wt. % doping where the Cu dissolution can be seen after 4000 h current load.

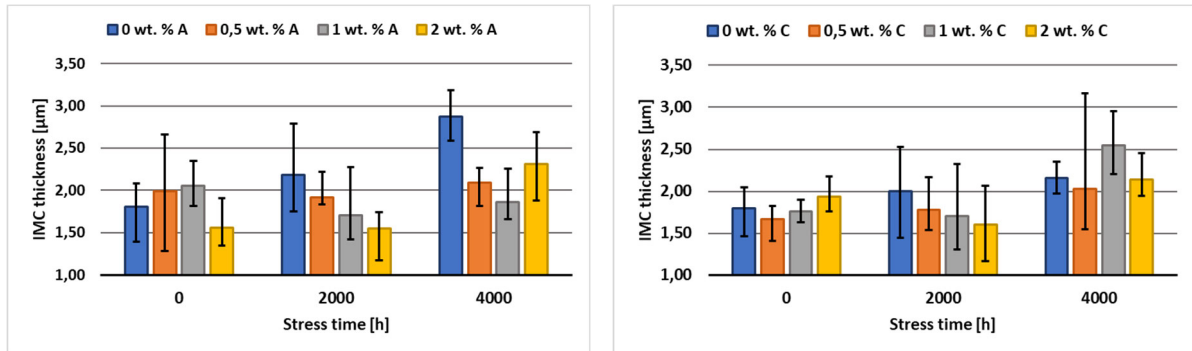


Figure 4-8 – IMC growth at anode side of resistors. Left: anode, right: cathode

4.3.4 Comparison of IMC growth with literature models

Besides the evaluation of the IMC layer thicknesses, comparison with models developed in literatures [28], [29] was also done. The results are shown on Figure 4-9 and Figure 4-10.

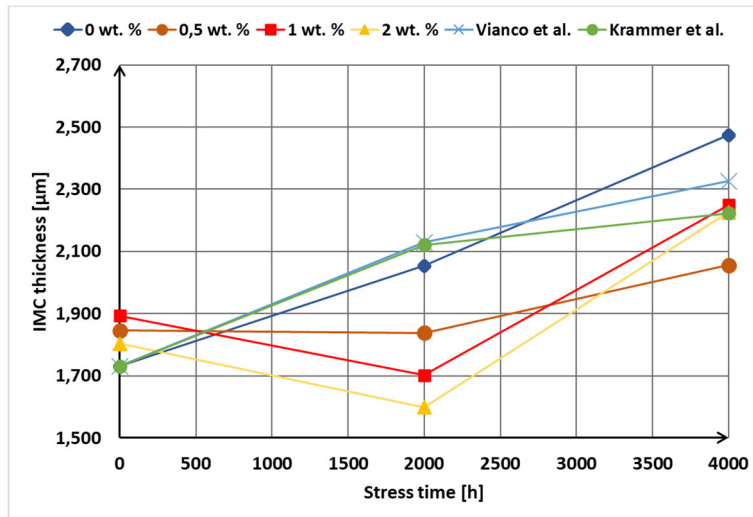


Figure 4-9 – IMC growth compared to theoretical models from [28], [29], anode and cathode side IMC thicknesses averaged as one data point

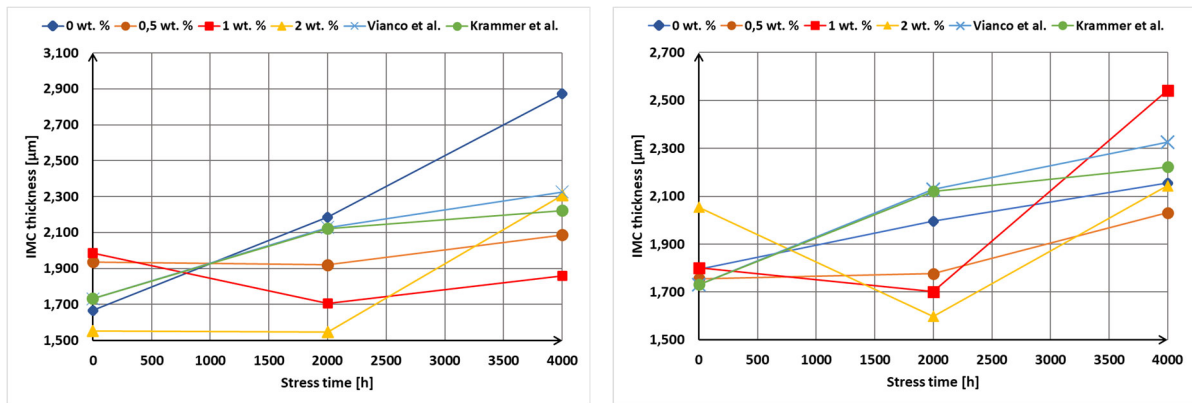


Figure 4-10 – IMC layer growth compared to theoretical models [28], [29], anode and cathode side treated separately. Left: anode, right: cathode.

Figure 4-9 shows the comparison with the theoretical models, when the anode and cathode thicknesses are averaged and treated as one group, Figure 4-10 shows the results compared with the theoretical model separately for the anode (left) and cathode (right). The equations for the theoretical models are presented in Equation 2-4 and Equation 2-5. For fitting of the models, the x_0 parameter, which is the starting thickness was set as 1,73 μm , which is the as-reflowed average IMC thickness for samples with 0 wt. % doping. The two theoretical models show good agreement with each other. The growth of the IMC in the case of the 0 wt. % doped samples is slightly lower, which could be the result of the lower temperature during aging. Both models were developed for aging above 100 $^{\circ}\text{C}$, and the test vehicles maximum temperature for my case was 80 $^{\circ}\text{C}$. This could result in the lesser growth of the undoped samples. The diagrams show that the doping of the solder joint at 0,5 wt. % is highly effective at reducing the IMC thickness. The doping level of 1 wt. % of the cathode shows high IMC growth after 4000 h, this could be the result of appearance of the Cu dissolution at 4000 h.

4.4 Microstructural damage around voids

During the stress test, some of the test vehicles were removed from the test at 1000 h, 2000 h and 4000 h. While no microstructural changes were observed for the samples at 1000 h, the samples at 2000 h had already started showing Cu dissolution, as stated previously. The test was run at 4 A current load, which would mean a current density of $2,2 \cdot 10^7$, assuming that the current is distributed uniformly around the nominal contact area of the 0402 resistors. This is a very high current density for the solder joints. Due to the geometrical setup of the solder joints (45° track-to-pad joining angle), the current density is expected to be locally significantly higher.

During stressing, voids would form in the Cu pads, due to the dissolution of the Cu material. As the voids cannot conduct current, the current would be forced around the void, raising the current density locally. This rise in current density creates extra Joule-heat in the joint resulting in microstructural damage. This damage can be seen on Figure 4-11.

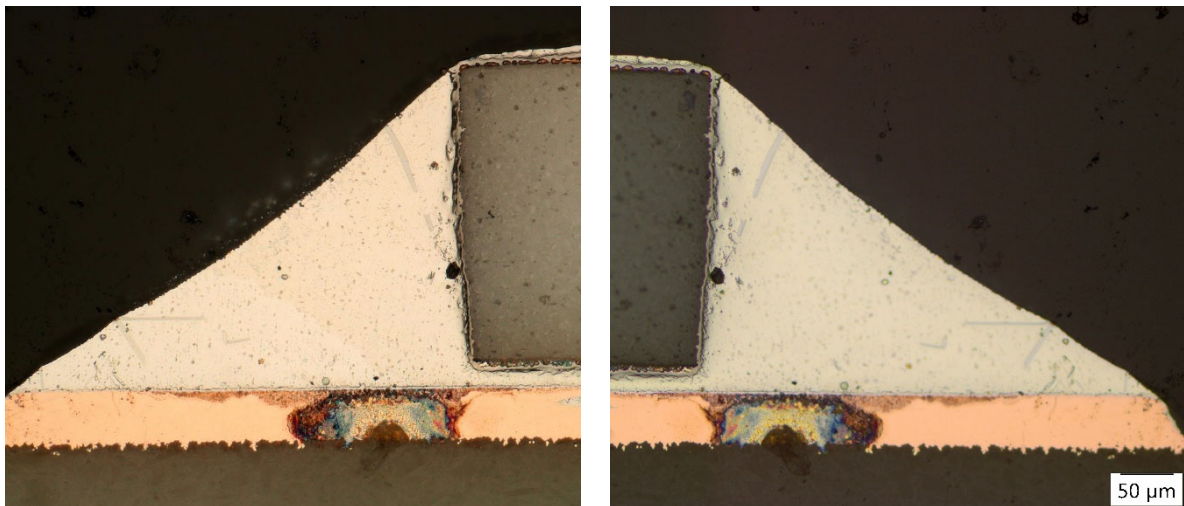


Figure 4-11 – Current density induced microstructural damage around voids. Left: anode of resistor, right: cathode of resistor.

The discoloration in the Cu pad on Figure 4-11 is most likely the result of a very high local current density, resulting in high local temperatures, leading to the damage of the Cu pad. This kind of damage can be seen on multiple images taken from the cross-sections of the 0402 samples. The damage of the Cu pad may cause the weakening of the joint. This may be one of the reasons why the shear strength of 0402 samples was reduced significantly after loading for 4000 h.

5 Conclusion

In this manuscript, an overview of the existing literature of electromigration in solder joints was presented. The necessary terms were defined and explained for focused application on the novel, previously not investigated lead-free, Fe NP-doped, current-stressing experiments. From the scientific summary, it can be clearly seen, that electromigration effects in small-scale solder joints pose a danger from a reliability perspective. Electromigration can lead to IMC thickening, Cu dissolution, voiding and recrystallization, resulting in reduced mechanical strength and earlier failure of solder joints.

After the literature review section, the measurement setup was presented. The test vehicles, each containing 15 samples of 0603 or 0402 resistors per PCB were connected in a daisy chain configuration. The samples were doped with 0, 0,5, 1 and 2 wt. % Fe NPs to improve the electromigration behaviour. The samples were stressed at 4 A current load, and were examined at the following stress times: 0 h (as reflowed), 1000 h, 2000 h and 4000 h. The test was done in a temperature-controlled chamber with active air cooling. Temperature was measured using thermocouples and environmental sensors, showing maximum board temperatures of ~ 80 °C, allowing the elimination of thermal effects based migration as cause of material transport and IMC evolution in the joints. The samples were examined using shear testing and cross-sectional analysis by SEM and optical microscopy, and the average IMC layer thickness was measured.

This work discusses that electromigration creates material transport, Cu pad dissolution and IMC thickening in the solder joint in the current, previously not investigated configurations as well (reduced effect of Joule-heating, 4 A load, applied Fe nanoparticles with flux-doping).

The reduced Joule-heat testing presented in this work shows that higher temperature (100 °C and above) is not necessary for the phenomena to occur. IMC layer thickening, Cu dissolution and shear strength decrease was clearly visible in all samples after current stressing. It is shown that the addition of Fe NPs by flux doping influences the electromigration behaviour of the solder joint. NP doping reduces IMC growth in the joint and Cu dissolution. Samples with 0,5 wt. % dopant level ~ 27 % reduction in IMC growth at the anode compared to undoped samples after 4000 h of testing, while at the cathode the improvement was ~ 5 %. Doping levels 1 wt. % and 2 wt. % show ~ 20 % and ~ 30 % reduction on the anode, but no significant reduction at the cathode, with 1 wt. % samples performing worse than undoped samples. Cu dissolution and voiding was completely inhibited by 0,5 wt. % doping, and only appeared at 1 wt. %

and 2 wt. % doping levels after 4000 h, while undoped samples began showing signs of Cu dissolution after 2000 h testing.

The average shear strength of 0,5 wt. % and 2 wt. % doped 0402 samples showed 13 % and ~5 % improvement in as-reflowed state compared to undoped samples. There was no meaningful difference for 1 wt. % doping. After 2000 h current load, the doped 0402 samples on average performed ~2,7-7,7 % better than undoped samples. After 4000 h testing, the average shear strength of doped samples was reduced significantly, with 0,5 wt. % doped and 1 wt. % doped samples performing worse than undoped samples. The nanoparticle doping increased shear strength for 0603 samples. After 4000 h current testing, the 2 wt. % doped samples showed ~16,5 % higher average shear strength compared to undoped samples.

The improvement of Cu dissolution and IMC layer thickness was found to be the largest for samples with 0,5 wt. % dopant level. This could be the result of the NPs being distributed uniformly at the solder-Cu interface at low dopant concentration, but agglomerating at higher dopant concentrations.

The future work can continue with the finite element modelling at box and at board level. The further decrease in component size (0201 and below), and micro/nano-alloyed solders are also in the future of future works.

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The research was initiated by an informal cooperation between TU Wien and BME, in the form of the investigation of Fe nanoparticle enhanced solders. The idea of Fe addition and the preparation of the paste was coming from Irina Wodak (TUW, PhD Student). Irina, with my supervisor and ETT laboratory colleagues oversaw the assembly process. I was responsible of the current stressing experimental setup, and the long-term stressing. The colleagues in EFI-Labs at ETT helped with the cross-section preparation physically. Optical images were taken at BME, SEM images were taken at TUW. Irina performed the shear-stress tests, I performed the SEM image processing and the results plotting, analysis, model-comparison and discussion presented in the current manuscript.

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