Study on Electromigration Effects and IMC Formation on Cu–Sn Films Due to Current Stress and Temperature

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Abstract: In this study, the effects of electromigration on a solder/copper substrate due to temperature and current density stress were investigated. The copper–tin (Cu–Sn) film samples were subjected under a fixed current and various heating conditions (130 °C and 180 °C) and current densities (different cross-sectional areas). The micro-structural changes and intermetallic compound (IMC) formation were observed, and failure phenomena (brittle cracks, voids, bumps, etc.) on the structures of samples were discussed. The results showed that the IMC thickness increased as the temperature and current density increased. Moreover, it was found that the higher the temperature and current density was, the greater the defects that were observed. By adjusting the designs of sample structures, the stress from the current density can be decreased, resulting in reduced failure phenomena, such as signal delay, distortion, and short circuiting after long-term use of the material components. A detailed IMC growth mechanism and defect formation were also closely studied and discussed.

Keywords: electromigration; intermetallic compound; current density

1. Introduction

Electronic packaging, although it is the last process to be done, is an indispensable part of the integrated circuit (IC) industry. It is responsible for connecting the integrated circuit with other electronic components. It also prevents the integrated circuit from being damaged by external forces, avoids chemical erosion and the influence of external noise, and increases the cooling path [1–3]. The range of packaging technology is very wide; it is applied in the fields of physics, chemistry, machinery, materials, etc. Packaging technology also uses a variety of materials, such as metals, ceramics, and polymers. Although packaging technology can prevent external forces from destroying the integrated circuit, there will always be unavoidable damage under normal use, such as joule heating damage and metal junction diffusion reaction and corrosion [4–8]. Joule heating occurs when the electron passes through the metal conductor inside the integrated circuit and produces lattice vibration due to collision with the atoms; the electrical energy and kinetic energy produced are converted into heat energy, which causes the solder temperature to rise. If the current passes through the metal conductor for a long time, overheating could occur, causing deformation, damage between the materials due to different expansion coefficients, and faster electromigration because of the thermal energy. The principle of electromigration dictates that when a current flows into the conductor, it moves from
the anode to the cathode, while the electrons flow from the cathode to the anode. As the electronic and kinetic energy increases as the current density increases, if the energy increases over its threshold, the atoms inside could move. The atoms will then move away from the cathode, producing a void, and will accumulate on the anode, causing protrusion. This abnormal diffusion will cause the lattice to produce dislocation. Ultimately, this will reduce the reliability of the IC and cause signal delay and distortion. Electromigration was discovered by Gerardin in 1861; since then, many people have studied this phenomenon [9–13]. In 1950, Seith and Wever indicated the relationship between the direction of current and the transport of matter. They observed that the direction of transport changes with charge carriers, so they made an indentation on the metal to observe the mass transfer of electromigration. From then on, this method has become the standard electromigration measurement method [14,15].

Electromigration is a mixed effect of electric power and thermal energy; it is mainly caused by electrostatic force and electronic wind resulting in mass transfer. Electrostatic force and electronic wind occur in opposite directions; their relationship can be described using formula (1), and electric wind can be calculated using formula (2).

\[ F_{driving} = \Sigma_i CM_i F_i = F_{el} + F_{wind} \]  \hspace{1cm} (1)

where

- \( F_{el} \) is the electrostatic force of the electric field,
- \( F_{wind} \) is the force of the electronic wind,

\[ F_{wind} = Z^*|e|E \]  \hspace{1cm} (2)

where

- \( Z^* \) is the number of effective electrons that cause atoms to move,
- \( e \) is the electron charge,
- \( E \) is the electric field.

The metal atoms move and carry energy. This energy comes from the atom itself and several external factors. As the atom moves, it may collide with other surrounding atoms, creating momentum transfer. The movement and diffusion of atoms is the main cause of electromigration effects. The drag force between electrons or electron holes and atoms also causes atoms to diffuse. Under the influence of electromigration effects, the diffusion of metal atoms can be expressed by using formula (3) [16].

\[ J = -D \frac{\partial C}{\partial x} + \Sigma_i CM_i F_i \]  \hspace{1cm} (3)

where

- \( D \) is the rate of diffusion,
- \( C \) is the atomic concentration,
- \( M \) is the atom mobility,
- \( F \) is the atomic diffusion driving force.

\[ -D \frac{\partial C}{\partial x} \] represents the chemical potential gradient,
\[ \Sigma_i CM_i F_i \] represents the sum of all atomic diffusion driving forces.

When two metals with different properties and chemical potentials are in contact for a long time, a metal interface reaction occurs; that is, their atoms diffuse with each other. Depending on the characteristics of the interface and the resulting interface reaction, a new equilibrium state can be achieved under specific conditions, producing intermetallic compounds (IMCs). At present, the mainstream soldering materials for electronic packaging processes are copper (Cu) and tin (Sn). When they are in contact for a long time, the change in temperature produces IMCs, such as Cu₆Sn₅ and Cu₃Sn. Tu et al. studied the diffusion phenomenon of Cu–Sn alloy and found that the IMC formation of Cu₆Sn₅ is mainly due to the diffusion of Cu atoms to the Sn layer [17]. Further, Yeh et al. studied the effect of current crowding in solder bumps on electromigration [18] and found that gaps and voids
will be produced first at a current crowded area; these gaps will start to accumulate, initially resulting in failure at the current crowded area. This study also confirmed that high current density makes solder bumps prone to failure. In addition, Tu and Liu et al. studied the effect of joule heating and current crowding on IC circuits and found that when the current is kept constant and the circuit sectional area is reduced, the current density will increase and joule heating and temperature will increase [7]. Previously, Chen et al. studied the electromigration effects of Cu–Sn IMC formation from different current inputs on a circuit with a fixed sectional area and found that a relatively high current will generate a high current density. This will cause the circuit to produce more holes, resulting in faster circuit failure [18]. However, because of the vast variety of modern integrated circuits in the market, the interconnecting IMC of ICs may experience electrical circuits with different sectional area. In order to understand the electromigration effect and IMC formation with different current stress caused by geometrical differences, this study designed an experiment that uses different cross-sectional settings resulting in changing current density and current crowded area of the IMC; thus, a circuit that with fixed input currents passing through different cross-sectional areas was employed to explore the effects of electromigration.

As previously mentioned, the present-day IC circuit encounters reliability problems after long-term use; thus, this study designed three samples with different cross-sectional areas, subjected them to the same current, and examined the resulting current density and temperature change. Two of the samples were trapezoidal in shape, and the other was rectangular. As the current passed through each sample at a certain length of time, joule heating, current density, and resulting electromigration effect were measured, analyzed, and compared with the other samples.

2. Design and Fabrication

This study examined the Cu and Sn intermetallic compound formation as a result of electromigration from current stress and heat. Figure 1 shows the sample production process. The samples were made of Ta/Cu/Sn thin films with a thickness of 250 nm, 20 µm, and 20 µm, respectively, deposited on the silicon substrate as an adhesion layer using high-power impulse magnetron sputtering (HiPIMS). Initially, HiPIMS was used to sputter a Ta film (250 nm thick) as the diffusion barrier layer. Next, DC power was used to sputter a Cu film (550 nm) as the seed layer. After, as shown in Figure 1b, the sample was placed in the plating solution and a Cu film (20 µm) was electroplated (detailed in Table 1). As presented in Figure 1c, 10 vol.% sulfuric acid was used to remove the surface oxides on the copper film surface, and then deionized water was used to remove the chemical residues attached to the surface; next, the sample was spin-coated with AZ P4620 positive photoresist, and patterning was done after. Finally, in Figure 1d, the sample was electroplated with a Sn film (20 µm) (detailed in Table 1) and photoresist was lifted off. Figure 1e presents the completed sample. After deposition, the sample was cut into three different shapes as shown in Figure 2.

This study deposited a Ta film to prevent Cu atoms from diffusing into the Si substrate. The diffusion activation energy of Cu and Sn is only 0.43 eV; therefore, Cu atoms can easily diffuse into the Si substrate. Previously, tantalum was found to be used as an excellent diffusion barrier between Cu and silicon substrate [19]; its atoms cannot easily diffuse to other materials, so it was deposited between Cu and Si to inhibit the diffusion of Cu atoms into the Si substrate.
Figure 1. The sample production process consisting of five major steps: (a) high-power impulse magnetron sputtering (HiPIMS) and DC power were used to sputter the sample with 250 nm Ta and 550 nm Cu films, respectively; (b) while in the plating solution, a 20 µm Cu film was electroplated onto the sample; (c) the samples were patterned with a positive photoresist; (d) a 20 µm Sn film was electroplated on the sample; and (e) the positive photoresist was removed.

Table 1. Conditions for electroplating tin and copper films.

| Acid Cu Plating Solution | Acid Sn Plating Solution |
|--------------------------|--------------------------|
| **Composition**          | **Percentage**           | **Composition** | **Percentage** |
| CuSO₄·5H₂O               | 22%                      | Organostannic  | 10%          |
| H₂SO₄                    | 9%                       |                 |              |
| Cl⁻                     | 6%                       | SNT-500        | 50%          |
| Cu-Additive             | 1%                       | pH             | <1           |
| pH                      | <1                       | pH             | 4            |

| Cu plating conditions    | Sn plating conditions   |
|--------------------------|-------------------------|
| Area of sample           | Area of sample          |
| 0.785 dm² (100 mm = 1 dm)| 0.594 dm² (100 mm = 1 dm)|
| Current                  | Current                 |
| 3.1 A                    | 0.3 A                   |
| Temperature              | Temperature             |
| 21 °C                    | 25 °C                   |
| Time                     | Time                    |
| 22.7 min                 | 80 min                  |
| Stirring                 | Stirring                |
| magnetic stirring         | magnetic stirring        |
Samples were subjected to a fixed current on its Sn film and heated at 130 °C and 180 °C. There were three experiments conducted in this study as shown in Figure 3; these were (1) thermal annealing test, (2) thermal annealing with constant electric current test, and (3) thermal annealing with constant electric current and varied current density (change in cross-sectional area) test. After, the microstructure changes in the sample or the growth trend of IMCs and the electromigration effects were observed.

3. Experimental Method

The sample was cut into three different shapes with different cross-sectional areas. Each was subjected to a fixed current on its Sn film and heated at 130 °C and 180 °C. There were three experiments conducted in this study as shown in Figure 3; these were (1) thermal annealing test, (2) thermal annealing with constant electric current test, and (3) thermal annealing with constant electric current and varied current density (change in cross-sectional area) test. After, the microstructure changes in the sample or the growth trend of IMCs and the electromigration effects were observed.

![Figure 2](image_url)  
**Figure 2.** The sample was cut into three different sizes: (a) 5:5 size; (b) 3:7 size; (c) 1:9 size; (d) actual samples.

![Figure 3](image_url)  
**Figure 3.** The test process for designing three different experiments.
3.1. Thermal Annealing Test

The experimental structure for thermal annealing test is shown in Figure 4. Samples were placed into the hot circulator oven for the thermal annealing test and the IMC growth was observed. The experimental time for the first sample was 3 days at 130 °C, and for the second, it was 4 days at 180 °C. After the experiment, the test samples were placed outside to cool down to room temperature.

![Figure 4. Thermal annealing test. (a) Structure diagram of heating and input current test; (b) experimental schematic diagram of heating and input current testing.](image)

3.2. Thermal Annealing with Constant Electric Current Test

Figure 5 presents the set-up for the second experiment. The test samples having a constant cross section with dimensions of 5 mm × 5 mm × 20 mm (5:5) were placed on the heating plate for heating, and a DC power supply was used to provide the current. One sample was heated at 130 °C and observed for 3 days and 4 days; while the other was heated at 180 °C and observed for 3 days and for 4 days as well. The current for both samples was fixed at 0.8 A. The samples were connected to a probe at both ends where current was allowed to flow. A thermocouple was utilized to observe the temperature while the sample was on the heating plate. After the tests, the samples were allowed to cool at room temperature. An optical microscope and FESEM were employed for metallographic observation.

![Figure 5. Path diagram of heat and current.](image)

3.3. Thermal Annealing with Constant Electric Current and Varied Current Density Test

As mentioned, the study was to explore the electromigration effect and IMC formation with different current stress caused by geometrical differences. The study designed samples with different cross-sectional settings of three kinds. Besides the constant cross-sectional test samples, the other two samples were trapezoidal in shape and had different cross-sectional areas. The dimensions of the samples were designed to systematically change the width of the sample from 5 mm × 5 mm × 20 mm (5:5) to 3 mm × 7 mm × 20 mm (3:7) and 1 mm × 9 mm × 20 mm (1:9). The set-up for the experiment
was similar to that of the second. Since the samples had different cross-sectional areas, the current input yielded different current densities. The changes in the samples are shown in Figure 2b,c.

The current density was calculated using the ANSYS Workbench finite element analysis software after the samples were subjected to heat and current. Figure 6a shows the structure of the 5 mm × 5 mm × 20 mm (5:5) Cu–Sn film sample. The simulation result indicated that the average current density in the front area was approximately $2.6 \times 10^5$ A/cm$^2$. Meanwhile, Figure 6b presents the structure of the 3 mm × 7 mm × 20 mm (3:7) Cu–Sn film sample. The simulation results indicated that the current densities of the r point and the w point were approximately $1.8 \times 10^5$ A/cm$^2$ and $3.8 \times 10^5$ A/cm$^2$, respectively. Figure 6c shows the structure of the 1 mm × 9 mm × 20 mm (1:9) Cu–Sn film sample. The simulation results indicated that the current densities of the r point and the w point were approximately $1.2 \times 10^5$ A/cm$^2$ and $7.8 \times 10^5$ A/cm$^2$, respectively. The simulation results are summarized in Table 2.

**Figure 6.** The current density distribution of the Cu–Sn thin film samples after being subjected to a fixed current of 0.8 A, for the (a) 5:5 sample; (b) 3:7 sample; and (c) 1:9 sample.

**Table 2.** The changes in the current density of the samples at different points.

| Test Sample Location | 5:5       | 3:7       | 1:9       |
|----------------------|-----------|-----------|-----------|
| r point              | $2.57 \times 10^5$ | $1.81 \times 10^5$ | $1.15 \times 10^5$ |
| s point              | $2.57 \times 10^5$ | $1.94 \times 10^5$ | $1.27 \times 10^5$ |
| t point              | $2.57 \times 10^5$ | $2.10 \times 10^5$ | $1.66 \times 10^5$ |
| u point              | $2.57 \times 10^5$ | $2.92 \times 10^5$ | $2.66 \times 10^5$ |
| v point              | $2.57 \times 10^5$ | $3.25 \times 10^5$ | $3.77 \times 10^5$ |
| w point              | $2.57 \times 10^5$ | $3.84 \times 10^5$ | $7.78 \times 10^5$ |
4. Results and Discussion

The study designed three sets of experiments, namely a (1) thermal annealing test, (2) thermal annealing with constant electric current test, and (3) thermal annealing with constant electric current and varied current density test. After the tests, the samples were closely examined, using EDS analysis for their IMC composition and SEM observation for thermal damage, IMC growth, and electromigration effects both in the anode and cathode of each test sample. Figure 7 presents SEM images and EDS analysis of the sample after fabrication; it appears that no IMCs were formed during the sample preparation process and that there was a clear interface between Cu and Sn.

4.1. Thermal Annealing Test

In the first experiment, the samples were heated at 130 °C and 180 °C, respectively, for 3 and 4 days. After EDS analysis and cross-sectional SEM, the IMCs formed in the sample heated at 130 °C were Cu₆Sn₅ with a thickness of 1.18 µm, Cu₃Sn with a thickness of 1.09 µm, and Cu₃Sn observed as holes in a small amount. Meanwhile, the IMCs formed in the sample heated at 180 °C were Cu₆Sn₅ with a thickness of 1.587 µm and Cu₃Sn with a thickness of 1.645 µm (see Figure 8a). After 3 days, the sample heated at 130 °C resulted in thicker IMC formation: Cu₆Sn₅ = 3.577 µm, Cu₃Sn = 1.764 µm, and Cu₃Sn observed as holes in a small amount. Similarly, after 4 days, the sample heated at 180 °C had thicker IMC formation: Cu₆Sn₅ = 4.565 µm and Cu₃Sn = 2.658 µm thick (see Figure 8b). As evident in the results, the higher the temperature of the sample and the longer it is heated, the thicker the IMC formation.
As the sample heated at 130 °C and cracks in the IMC layer of the sample heated at 130 °C were few. The IMC formation in the samples’ anode and cathode ends were monitored and measured. As shown in Figure 9, the holes and cracks in the IMC layer of the sample heated at 130 °C were few. The resulting IMC formations and their corresponding thickness for the sample heated at 130 °C are summarized in Table 3.

4.2. Thermal Annealing with Constant Electric Current and Current Density (Uniform Cross-Sectional Areas)

In this experiment, two 5:5 samples (constant cross-section samples) were heated and subjected to a current fixed at 0.8 A. One sample was heated at 130 °C and was observed after 3 days and 4 days; the other was heated at 180 °C and was also observed after 3 days and 4 days. The IMC formation in the samples’ anode and cathode ends were monitored and measured. As shown in Figure 9, the holes and cracks in the IMC layer of the sample heated at 130 °C were few. The resulting IMC formations and their corresponding thickness for the sample heated at 130 °C are summarized in Table 3.

Figure 8. Intermetallic compound (IMC) formation after thermal annealing: (a) sample heated at 130 °C for 3 days; (b) sample heated at 180 °C for 4 days.

Figure 9. SEM images of 5:5 sample heated at 130 °C and subjected to a current of 0.8 A. (a) Anode side (indicated on red circle) for 3 days; (b) Cathode side for 3 days; (c) Anode side for 4 days; (d) Cathode side for 4 days.
Table 3. The IMC formation and their corresponding thickness in the sample heated at 130 °C and subjected to a current of 0.8 A.

| IMC   | Anode 3 Days | Anode 4 Days | Cathode 3 Days | Cathode 4 Days |
|-------|--------------|--------------|----------------|----------------|
| Cu₆Sn₅| 1.71         | 2.02         | 1.6            | 1.67           |
| Cu₃Sn | 1.56         | 1.85         | 1.39           | 1.51           |
| Total IMC | 3.27       | 3.87         | 2.99           | 3.18           |

For the 5:5 samples with constant current and heated at 180 °C, it was observed that the IMC formation was considerably thicker after 3 days and 4 days of observation. The high temperature provided Cu₆Sn₅ with great growth energy; and because Cu₃Sn growth was controlled by Cu₆Sn₅, the latter was thicker than the former. Table 4 and Figure 10 show the IMC formations and their corresponding thickness in the sample heated at 180 °C. It was also observed that the IMC in the anode was thicker than that in the cathode end. This is because the atoms in the cathode migrated out, while those in the anode accumulated on the site.

Table 4. The IMC formation and their corresponding thickness in the sample heated at 180 °C and subjected to a current of 0.8 A for the 5:5 sample.

| IMC   | Anode 3 Days | Anode 4 Days | Cathode 3 Days | Cathode 4 Days |
|-------|--------------|--------------|----------------|----------------|
| Cu₆Sn₅| 7.65         | 7.68         | 5.3            | 6.56           |
| Cu₃Sn | 2.69         | 4.67         | 2.69           | 3.29           |
| Total IMC | 10.34      | 12.35        | 7.99           | 9.86           |

Figure 10. SEM images of 5:5 sample heated at 180 °C and subjected to a current of 0.8 A. (a) Anode side (indicated on red circle) for 3 days; (b) Cathode side for 3 days; (c) Anode side for 4 days; (d) Cathode side for 4 days.
4.3. Thermal Annealing with Constant Current and Varied Current Density (Different Cross-Sectional Areas)

In the last experiment, the samples used had different cross-sectional areas (3:7 and 1:9) and were subjected to a current of 0.8 A. Both were heated at 130 °C and 180 °C separately for 3 and 4 days. The current density was analyzed using the finite element method software ANSYS. The results showed that after being heated at 130 °C, the current density at the 1 mm end of the 1:9 sample was $1.1 \times 10^6$ A/cm$^2$, at the 3 mm end of the 3:7 sample it was $1.0 \times 10^6$ A/cm$^2$, at the 7 mm end of the 3:7 sample it was $5.4 \times 10^5$ A/cm$^2$, and at the 9 mm end of 1:9 sample it was $4.4 \times 10^5$ A/cm$^2$. Since the samples had different cross-sectional areas, the resulting current density and IMC formation were also different. The IMCs and their corresponding thickness formed after 3 days and 4 days in the anode end of the samples heated at 130 °C are shown in Table 5 and Figure 11, while those in the cathode end are shown in Table 6 and Figure 12.

| IMC   | Anode end (130 °C) |   |   |   |   |   |   |   |
|-------|--------------------|---|---|---|---|---|---|---|
|       | Position          | 1 mm | 3 mm | 7 mm | 9 mm | 1 mm | 3 mm | 7 mm | 9 mm |
|       | 3 Days            |     |     |     |     |     |     |     |     |
|       | 4 Days            |     |     |     |     |     |     |     |     |
| Cu$_6$Sn$_5$ | 2.09 | 1.81 | 1.63 | 1.54 | 2.73 | 2.13 | 2.01 | 1.66 |
| Cu$_3$Sn | 2.27 | 2.15 | 1.85 | 2.14 | 2.05 | 1.92 | 1.96 | 1.75 |
| Total IMC | 4.36 | 3.96 | 3.48 | 3.68 | 4.78 | 4.05 | 3.97 | 3.41 |

**Table 5.** The IMC formation and their corresponding thickness in the anode end of the sample heated at 130 °C and subjected to a current of 0.8 A.

**Figure 11.** SEM images of various samples heated at 130 °C and subjected to a current of 0.8 A after 4 days. (a) Anode ends (indicated on red circle) on the 1mm side of 1:9 sample; (b) Anode ends (indicated on red circle) on the 3mm side of 3:7 sample; (c) Anode ends (indicated on red circle) on the 7mm side of 3:7 sample; (d) Anode ends (indicated on red circle) on the 9 mm side of 1:9 sample.
Table 6. The IMC formation and their corresponding thickness in the cathode end of the sample heated at 130 °C and subjected to a current of 0.8 A.

| IMC   | Cathode End (130 °C) |
|-------|----------------------|
|       | 3 Days | 4 Days |
| Position | 1 mm | 3 mm | 7 mm | 9 mm | 1 mm | 3 mm | 7 mm | 9 mm |
| Cu₆Sn₅ | 1.84  | 1.59 | 1.24 | 1.39 | 1.84 | 1.32 | 1.48 | 1.21 |
| Cu₃Sn | 2.04  | 1.98 | 2.03 | 1.74 | 1.86 | 1.74 | 1.64 | 1.70 |
| Total IMC | 3.88 | 3.57 | 3.27 | 3.14 | 3.7  | 3.06 | 3.12 | 2.91 |

Figure 12. SEM images of various samples heated at 130 °C and subjected to a current of 0.8 A after 4 days. (a) Cathode ends (indicated on red circle) on the 1 mm side of 1:9 sample; (b) Cathode ends (indicated on red circle) on the 3 mm side of 3:7 sample; (c) Cathode ends (indicated on red circle) on the 7 mm side of 3:7 sample; (d) Cathode ends (indicated on red circle) on the 9 mm side of 1:9 sample.

The resulting IMC formations in the anode end of the samples with different cross-sectional areas heated at 180 °C after 3 days and 4 days are shown in Table 7 and Figure 13, and those in the cathode end are shown in Table 8 and Figure 14.
Table 7. The IMC formation and their corresponding thickness in the anode end of the sample heated at 180 °C and subjected to a current of 0.8 A.

| IMC       | Anode End (180 °C) |   |   |   |   |   |   |   |
|-----------|---------------------|---|---|---|---|---|---|---|
|           | 3 Days              | 4 Days                      |
| Position  | 1 mm | 3 mm | 7 mm | 9 mm | 1 mm | 3 mm | 7 mm | 9 mm |
| Cu₆Sn₅    | 9.18 | 6.98 | 7.16 | 9.98 | 9.51 | 8.17 | 9.02 | 8.38 |
| Cu₃Sn     | 3.92 | 3.38 | 3.06 | 3.17 | 3.99 | 4.63 | 4.16 | 3.7  |
| Total IMC | 13.11 | 10.99 | 10.22 | 9.98 | 13.51 | 12.8 | 12.19 | 12.08 |

Figure 13. SEM images of various samples heated at 180 °C and subjected to a current of 0.8 A after 4 days. (a) Anode ends (indicated on red circle) on the 1 mm side of 1:9 sample; (b) Anode ends (indicated on red circle) on the 3 mm side of 3:7 sample; (c) Anode ends (indicated on red circle) on the 7 mm side of 3:7 sample; (d) Anode ends (indicated on red circle) on the 9 mm side of 1:9 sample.

Table 8. The IMC formation and their corresponding thickness in the cathode end of the sample heated at 180 °C and subjected to a current of 0.8 A.

| IMC       | Cathode End (180 °C) |   |   |   |   |   |   |   |
|-----------|----------------------|---|---|---|---|---|---|---|
|           | 3 Days              | 4 Days                      |
| Position  | 1 mm | 3 mm | 7 mm | 9 mm | 1 mm | 3 mm | 7 mm | 9 mm |
| Cu₆Sn₅    | 5.56 | 5.34 | 5.3  | 3.38 | 6.14 | 6.24 | 5.36 | 5.03 |
| Cu₃Sn     | 3.27 | 2.99 | 1.84 | 2.83 | 3.44 | 3.37 | 4.05 | 3.66 |
| Total IMC | 8.83 | 8.34 | 7.13 | 6.21 | 9.58 | 9.61 | 9.41 | 8.69 |
Table 8. The IMC formation and their corresponding thickness in the cathode end of the sample heated at 180°C and subjected to a current of 0.8 A.

| Position | Cu6Sn5 | Cu3Sn | Total IMC |
|----------|--------|-------|-----------|
| 1 mm     | 5.56   | 3.27  | 8.83      |
| 3 mm     | 5.34   | 2.99  | 8.34      |
| 7 mm     | 5.3    | 1.84  | 7.13      |
| 9 mm     | 3.38   | 2.83  | 6.21      |

Figure 14. SEM images of various samples heated at 180°C and subjected to a current of 0.8 A after 4 days. (a) Cathode ends (indicated on red circle) on the 1 mm side of 1:9 sample; (b) Cathode ends (indicated on red circle) on the 3 mm side of 3:7 sample; (c) Cathode ends (indicated on red circle) on the 7 mm side of 3:7 sample; (d) Cathode ends (indicated on red circle) on the 9 mm side of 1:9 sample.

Based on the results, the IMC formation was thicker in the samples heated at 180°C than those heated at 130°C. This is because the diffusion energy was greater in the former than the latter (see Tables 5 and 6). Moreover, similar with the second experiment, it was found that the IMC layer formed was thicker at the anode end than at the cathode end. The reason for this is that the temperature of the anode end was higher resulting in a higher thermal energy than that of the cathode end (see Figure 15) [4]. In terms of current density, it was found that the IMC layer formed in the sample heated at 180°C was considerably greater than those in the sample heated at 130°C. Further, regardless of the temperature, the growth of the IMC layer at the cathode end was not as obvious as that at the anode end. This is consistent with the result in experiment 2, wherein the IMC growth was more obvious at the anode end.

As observed in Figures 11 and 12 (samples heated at 130°C) and Figures 13 and 14 (samples heated at 180°C), there were more holes and cracks at the cathode ends than at the anode ends. It appears that at the high electric current density, the direction of electron flow is from the cathode end towards the anode end; while electromigration enhances atomic flux to move towards the anode to thicken the IMC thickness and causes holes and cracks at the cathode end [20].

Consequently, it was found that the current densities on the anode ends of the 1 mm end of the 1:9 sample and the 3 mm end of the 3:7 sample were relatively higher than that of the 7 mm end of the 3:7 sample and the 9 mm end of the 1:9 sample. This resulted in the former having a thicker IMC formation than the latter. There were also fewer defects at the 7 mm end of the 3:7 sample and the 9 mm end of the 1:9 sample at the anode ends. Figure 16c, d shows the degree of IMC growth in the samples.
Figure 15. The temperature read-out of the sample located at the (a) anode heated at 130 °C with input current; (b) cathode heated at 130 °C with input current; (c) anode heated at 180 °C with input current; (d) cathode heated at 180 °C with input current.

Figure 16. Analysis of the degree of IMC growth in the samples with different cross-sectional areas. (a) Anode end; (b) cathode end; (c) samples heated at 130 °C; (d) samples heated at 180 °C.
Blech [9,10], Huntington [13], and Black [21] illustrated that the electromigration mechanism is the massive atomic diffusion driven by a high electric current density in the direction of electron flow. While electromigration drives atomic flux to the anode side, an equal flux of vacancies diffuses to the cathode side. This study considers both atomic flow and electric carrier flow as well as their interaction of thermal energy. We found that as the cross-section decreased on the sample anode ends from 9 mm and 7 mm down to 3 mm and 1 mm, the density of the electrons increased. This would increase the driving force in Equation (1) and the atom diffusion flux in Equation (3); the increase in the driving force indicates that the atomic diffusion capacity $J$ would also increase. Therefore, because the atomic diffusion capacity increases, the atoms move from the cathode to the anode and finally cause voids and cracks at the cathode end and a stacking phenomenon at the anode end. If the flux of vacancies cannot be absorbed by the IMC structure, the vacancies reach saturation near the cathode side and the nucleation of voids occurs. The growth of the void corresponding to the flux of vacancies will eventually end up as an open interconnected circuit and cause failure [22,23].

However, it appeared that with the cross-section increases on the sample anode ends from 1 mm and 3 mm up to 7 mm and 9 mm, the density of the electrons decreased. Given the circumstances of the samples tested in this study, it can be assumed that the widened cross-section prevented additional atoms from moving toward the anode side and electromigration effects were reduced as a result. Moreover, according to Blech and Tu [10,13], an electromigration back current stress gradient exists where the highest compressive current stress can be found near the anode side due to the accumulation of atoms. The results demonstrate that the electromigration compressive current stress could be annihilated.

In summary, regardless of the temperature or the current density, it was found that the IMC formation was always thicker at the anode end than at the cathode end, even after 4 days of heating and being subjected to the current. This indicates that the high electronic current density causes electromigration and atoms to accumulate at the anode end, resulting in greater thermal energy than that at the cathode end. Moreover, the movement causes the atoms in the metal to gain more heat energy, increasing their driving force and resulting in a thicker IMC layer at the anode end and voids at the cathode end.

5. Conclusions

This study investigated the growth rate of IMCs under a fixed current and varied temperatures and cross-sectional areas. The results showed that high temperature and high current density affect the degree of IMC formation. When the Cu–Sn film was heated at 130 °C and 180 °C, the growth of Cu$_3$Sn and Cu$_6$Sn$_5$ differed due to thermal diffusion. In addition, it was found that the thickness of the IMC layer is proportional to the heating time and the temperature; that is, the longer the film is heated and the higher the temperature is, the greater and the thicker the growth of the IMC layer. This research also found that the IMC layer formed at the anode end was thicker than that at the cathode end, and under the same heating conditions, the temperature difference between the anode end and the cathode end was between 20 °C and 25 °C. This is because the current at the anode end caused a large number of electrons with high current density, resulting in higher temperature, which in turn made the IMC layer grow faster and thicker. In addition, as shown in the SEM photos provided, the IMC layer at the cathode end had holes, cracks, and other failure phenomena. This is because a large number of metal atoms at the cathode end migrated towards the anode end after being subjected to the current for a long time. Finally, it was found that the samples with greater current density had thicker IMC layers and had more holes and cracks at the cathode end. On the contrary, the samples with lower current density had relatively thin IMC layers and had fewer holes and cracks at the cathode end.

This shows that the current density affects the reliability of the IC circuit and the welding material. Therefore, when designing electronic packaging in the future, under a fixed current, the conductive sectional area of the flip chip solder ball should be slightly modified and enlarged to reduce the current
density crowding caused by the current flowing into the structure. By reducing the current density, the reliability and service life of electronic products can be improved.

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