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Lifetime Prediction of Electrochemical Ion Migration with Various Surface Finishes of Printed Circuit Boards

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Electrochemical ion migration (ECM) can be generated by the electrochemical reaction between the anodic and cathodic electrodes of an electric circuit in the case of temperature, humidity and applied voltage. ECM can finally induce a malfunction of electronics due to precipitation of metallic ions in the cathode. In this work, we study the failure mechanism based on the identifying stress factor of ECM to occur and the accelerated life prediction of ECM occurrence. The modified Eyring model, which includes a stress model (temperature, humidity and voltage), is utilized to accelerate the life prediction of ECM. To obtain the temperature and humidity coefficient factors of ECM failure, an accelerated life test is conducted with a more than 50% failure of five types of test conditions, namely, 85°C/75% RH, 65°C/85% RH, 85°C/85% RH, 75°C/85% RH and 85°C/95% RH. The failure criterion of insulation resistance between the conductors is less than or equal to 10^7 Ω. In situ monitoring of surface insulation resistance is performed throughout the temperature-humidity-bias tests for over 2600 h. From these results, we deduce the temperature and humidity coefficients of the acceleration model for predicting ECM time-to-failure in electroless nickel-immersion gold (ENIG) surface finish conductors covered with a solder mask. In addition, the electrochemical oxidation and reduction mechanisms of ECM are examined by physics-of-failure. Finally, we predict the B_{10} life for ECM to occur on a FR-4 printed circuit board with an ENIG surface finish in use environment.

Key words: Electrochemical ion migration (ECM), dendrite, printed circuit board (PCB), migration stress factor, failure analysis, acceleration factor

INTRODUCTION

Pb-free soldering technology has given rise to the need for electrochemical ion migration (ECM) research. As higher glass transition temperature (Tg) printed circuit boards (PCB) are needed in Pb-free soldering, the PCB materials of most electronics and automotive electronics have been exchanged with higher Tg PCB. If Pb-free solder can be applied in harsh environments for electronics, the replacement of PCB raw materials is a primary factor to consider. In addition, the current technology in mobile electronic assemblies is geared towards further miniaturization, more pin counts, finer line patterns, thinner and lighter bodies, higher frequency in signal integrity and higher speeds in signal propagation.[1–3] However, the risk of ECM failure increases with acceleration of the fine pitch and spacing of conductors in electronic packages and modules.

The ECM phenomenon, which is defined as the growth of conductive metal filaments on a PCB under the influence of a DC voltage bias, is one of the failure mechanisms of electronics.[3–5] ECM

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failure due to the growth of metal filaments (dendrites) may occur at an external surface, an internal interface or through the bulk material of laminate, and finally, may drive a short-circuit failure of electronic assemblies. The dendrite growth is by electrodeposition from a solution containing metal ions dissolved from the anode, transported by the electric field and redeposited at the cathode.[5] For ECM to occur between conductive electrodes across an insulating circuit board surface, three conditions, namely electrical carriers, water or relative humidity and electrical potential, must be met simultaneously. If the electrical carriers, such as ions, must be present, water or humidity must also be present to dissolve the ionic materials and sustain them in their mobile ionic state. Furthermore, an electric potential between the electrodes is needed to establish an ionic current in the water layer.[5]

The ECM phenomenon has been studied for a long time, but this is related to the failure mechanism and the relative risk comparison with surface finishes of conductors. The assessment for ECM to occur requires very long test durations. Normally, the Institute for Interconnecting and Packaging Electronic Circuits (IPC) standard calls for a 500 h test duration, but this is a very long period for industry to obey the IPC recommendation. Therefore, the electronics industries have demanded research into the ECM failure phenomenon and its accelerated life prediction method. Thus, this study investigated ECM failure and validated its failure stress on FR-4 PCB under temperature-humidity-bias (THB) testing. This research excludes phenomena such as field induced metal transport in semiconductors and the diffusion of products arising from metallic corrosion, such as conductive anodic filament (CAF). Based on these results, stress factors for accelerated life test (ALT) of ECM have been confirmed. The modified Eyring model,[6–9] composed of temperature, humidity and voltage stress, was utilized for ECM lifetime prediction. Finally, we have accomplished the THB test as an ALT method and obtained the acceleration factor (AF), temperature and humidity coefficients of the acceleration model for predicting ECM time-to-failure in electroless nickel-immersion gold (ENIG) surface finish conductors covered with a solder mask. These results will be helpful in predicting the lifetimes of electronics due to ECM failure within shorter testing durations.

EXPERIMENTAL PROCEDURE

Stress Factor Validation Testing

To validate the ECM failure stresses, such as temperature, humidity, conductor spacing, bias voltage, and conductor surface finish, THB validation testing was accomplished to determine the contribution of the stress factors affecting the FR-4 PCB (glass fiber and epoxy resin system), as shown in Table I. Figure 1a shows the THB test specimen which size was 20.0 (L) $\times$ 6.5 (W) $\times$ 2.0 (t) mm. The overlaying length of the anode and the cathode conductors in the PCB was 15.7 mm. In situ monitoring of surface insulation resistance (SIR) was performed throughout these THB tests for 1000 h using an insulation degradation evaluation system (SIR-12 system, ETAC Co., Japan) as shown in Fig. 2. The dendrite was identified with scanning electron microscopy (SEM) and energy dispersive x-ray spectroscopy (EDS).

Accelerated Life Test

From stress factor validation testing results, we have defined the stress factor for ECM to occur as a function of temperature, humidity and voltage. To obtain the temperature and humidity coefficients, five types of THB test conditions were used, namely, 85°C/75% RH, 65°C/85% RH, 85°C/85% RH, 75°C/85% RH and 85°C/95% RH. The FR-4 PCB with an ENIG surface finish covered with a solder mask in a 0.1 mm conductor spacing (Fig. 1b) under temperature, humidity and voltage stress factors was utilized for the ALT, as shown in Table II. The failure criterion of insulation resistance between the conductors was less than or equal to 1×10^{-6} Ω. The surface insulation resistance between the conductors was continuously monitored every 40 μs with a THB test system for 2666 h.

RESULTS AND DISCUSSION

Stress Factor Validation

The insulation resistance between the conductors continuously during THB testing was measured. When ECM occurred for the samples, we observed that the SIR dramatically dropped and we decided on this point to be the failure due to the dendrite formation. Figure 3 shows the optical images of dendrite formation of Cu, Ag, SP and SAC305 surface finishes with different conductor spacing after stress factor validation testing (THB test) for 1000 h. Simultaneously, the SIR of all types of test specimens in Fig. 3 was continuously measured (Fig. 4). The short-circuit failure between conductors occurred due to dendrite growth from the cathode to the anode. The ECM failure time was different with different surface finishes and spacing. Figures 5 and 6 show the dendrite formation due to ECM occurrence in the SAC305 and Cu conductor after THB testing for 1000 h. In the case of the Cu conductor, Cu was precipitated to the cathode and formed the dendrite. The growth direction is from the cathode to the anode. In the anode, Cu was consumed due to the metal oxidation reaction and the metal oxide was reduced to metal ions in the cathode, with metal ions finally forming the dendrite. From the EDS mapping and line profile results of the SAC305 surface finish, the elements of the dendrite were mainly Cu and Ag, with Sn also

Table I. Test method and specification of THB test

Test method	IPC-TR-476, JIS-Z-3197
Test conditions	60°C, 90% RH
Bias voltage	DC 6.5 V
Surface finishes	Cu, Ag, Sn-37Pb (SP) and Sn-3.0Ag-0.5Cu (SAC 305)
Conductor spacing	0.1, 0.318, 0.5 and 1.0 mm/Comb Pattern
Measurement	In situ monitoring of surface insulation resistance
Failure criteria	$< 10^6\ \Omega$
Test duration	1000 h

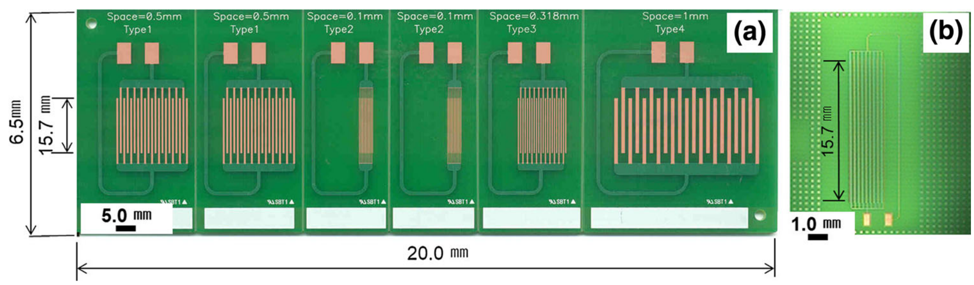

Fig. 1. Photographs of comb pattern specimen for testing of (a) ECM stress factor validation and (b) ALT.

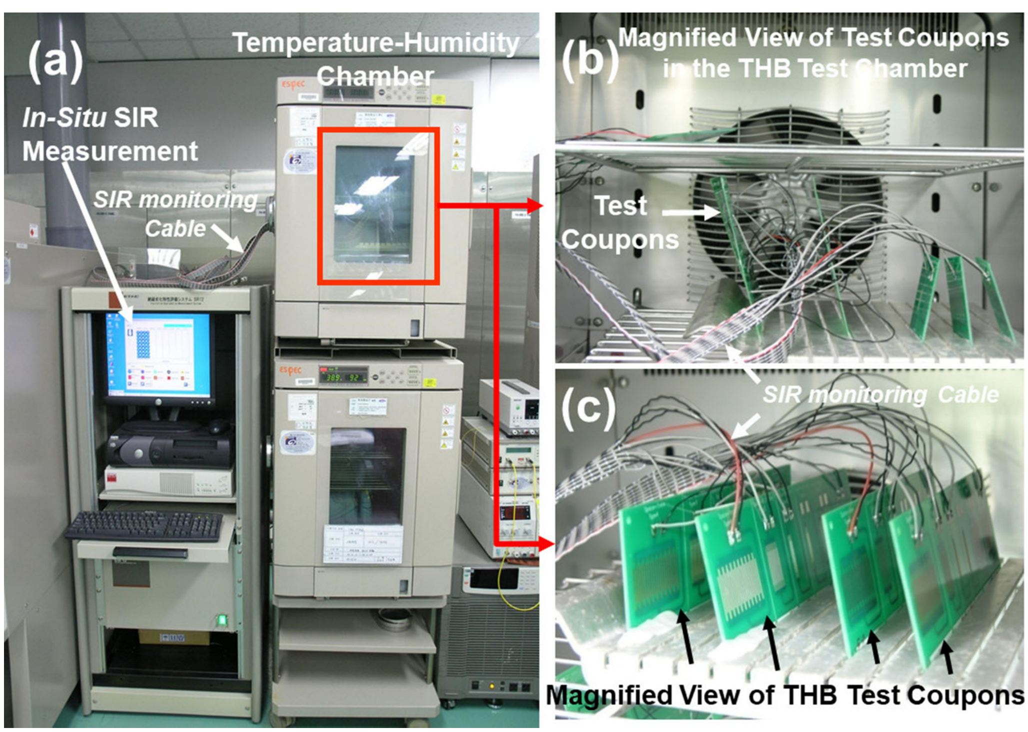

Fig. 2. Photographs of (a) temperature-humidity-bias test set-up and magnified view of (b) inner chamber and (c) test coupon.

detected on the conductor spacing. The Cu dendrite grew up from the cathode to the anode and finally induced the circuit shortage. These results mean that the conductor material was diffusing from the anode to the cathode. In addition, Cu which was the circuit material was migrated simultaneously. This phenomenon caused by drying up the surface finish material and exposing the Cu surface. The susceptibility order for ECM to occur with various surface finishes and spacing was Cu 0.1 mm (95.8752 h) > Sn37Pb 0.1 mm (99.9086 h) > SAC305 0.318 mm (105.6336 h) > Ag 0.318 mm (112.7419 h) under

Table II. Specification of accelerated life test samples

PCB material, layer and dimension	FR-4/12 layers/20.0 (L) × 6.5 (W) × 2.0 (t) mm
Conduct width and spacing	0.1 mm
Surface finish	Electroless nickel-immersion gold (ENIG)
Solder mask coating	Modified epoxy acrylate (t = 12 μm) (PSR4000 SP09MH, spray type)
Sample size	Ten samples for every condition
Test conditions	① 85°C, 75% RH ④ 65°C, 85% RH ② 85°C, 85% RH ⑤ 75°C, 85% RH ③ 85°C, 95% RH
Bias voltage	DC 100 V
Measurement	In situ monitoring of surface insulation resistance at every 40 ms
Failure criteria	$< 10^7$ Ω
Test duration	2666 h

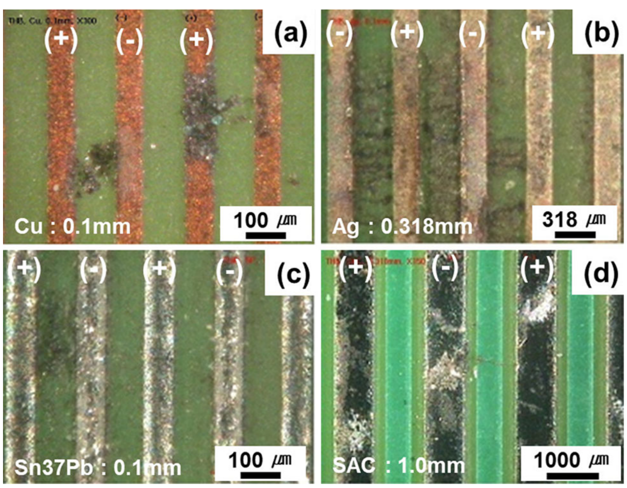

Fig. 3. Optical images of comb pattern sample with different surface finishes and spacing after stress factor validation testing (THB test) for ECM: (a) Cu, 0.1 mm, (b) Ag, 0.318 mm, (c) Sn-37Pb, 0.1 mm, and (d) SAC305, 1.0 mm.

the THB test. From these results, we know that the stress factors for ECM occurrence are temperature, humidity, surface finish materials, spacing and bias voltage. Consequently, it is difficult to distinguish the susceptibility order for ECM to occur. However, the THB test method was very efficient for comparing with conductor materials, spacing and other factors affecting the ECM.

Failure Mechanism of ECM

When a DC bias voltage is applied to the conductors and relative humidity exists, the metal can be oxidized with exhausting the anodic material and migrating to the cathode. Simultaneously, dendrite formation can be generated because a positive charged metal ion is reduced and precipitated to the cathode, finally leading to circuit shortage.[10–17] Figure 7 shows a schematic diagram of the ECM occurrence mechanism. The ECM phenomenon can be explained by metal ions being transferred from one metal electrode to the opposite metal electrode under electric fields. There are three processes leading to ECM. The first process is the anodic reaction (metal dissolution, Eq. 1), the second process is the cathodic reaction (metal or metal oxide deposits, Eq. 2) and the ternary process is the inter-electrode reaction (metal oxide deposits, Eq. 3).[7,10,11] The first and second reactions are thought to be mechanisms leading to dendrite formation. Metal dissolved at the anode is deposited on the cathode. Thus, these dendrites consist of pure metal or metal oxide deposits growing toward the cathode. The first and second reactions are all thought to be mechanisms leading to CAF formation. Considering the mechanism by the type of reaction, we find that the electrolytic reaction of water causes the area around the anode to become acidic due to H^+ ions forming from the anodic reaction equation, while the area around the cathode becomes alkaline due to OH^- ions forming from cathodic and inter-electrode reactions.[10–17] As shown in Fig. 7, metallic ion migration process was schematically explained the following four steps. The first is water adsorption and diffusion on the board surface. The second stage is a change in pH due to the electrolysis of water and the third stage is copper electrode elution and copper ion diffusion. Finally, electron transfer and ion migration occurrence (reduction). When ion migration occurs, ionization of metal ions occurs on the surface of the anode, and metal cations are present on the surface, thereby reducing the pH around the anode and accelerating the ionization reaction. The ionized metal ion is formed as a metal oxide or a metal hydrate by the water present between the electrodes and is transported to the anode. In the cathode, the metal ion is reduced by the reduction reaction to form dendrite. Therefore, the moving species from anode to cathode are metal oxide (MO_x) and metal hydroxylation ($M(OH)_x$) between inter-electrodes. For this process to occur in the circuit, electrical power must be applied in the circuit board. Thus,

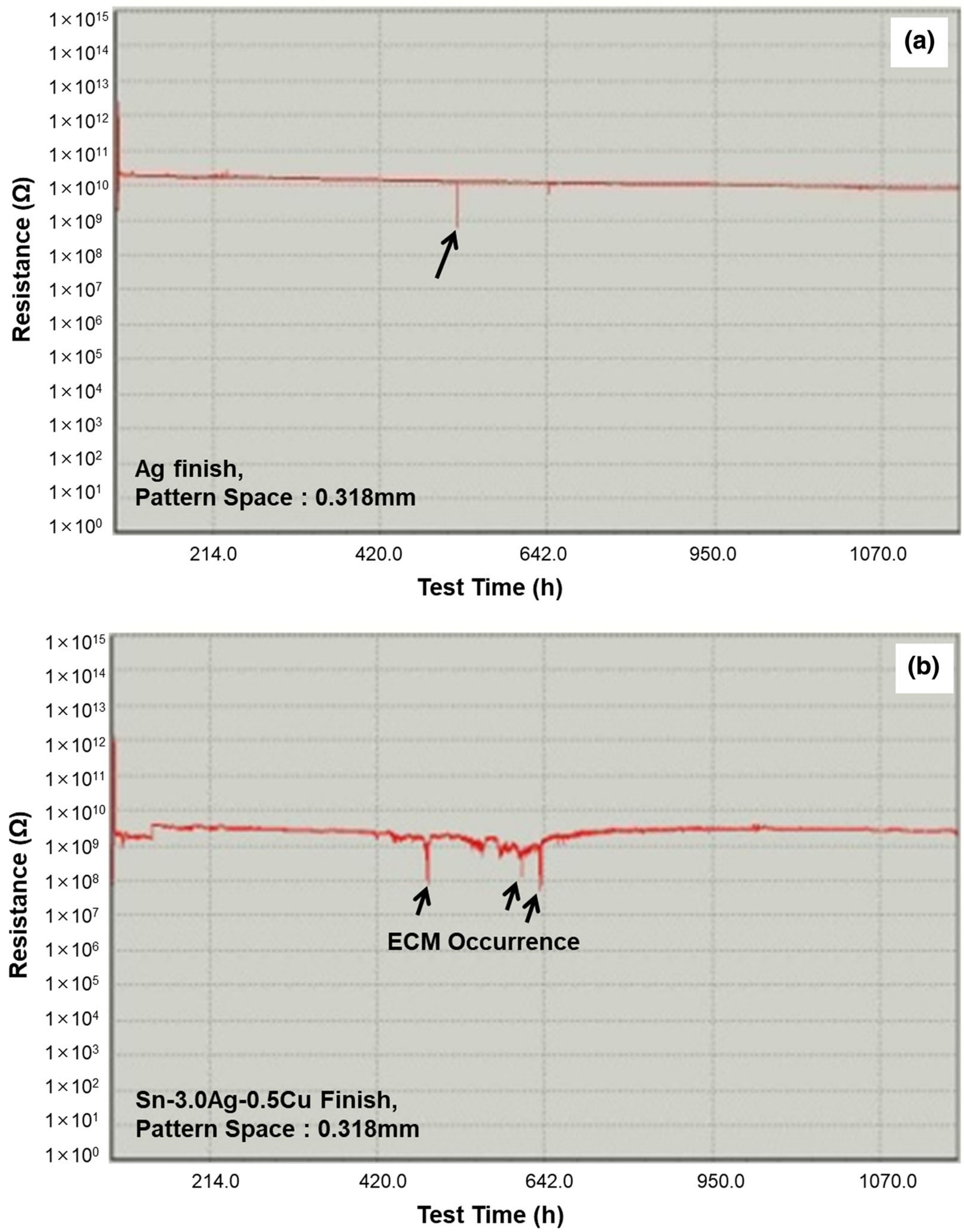

Fig. 4. In situ monitoring results of SIR for 0.318 mm spacing of (a) Ag and (b) SAC305 conductors.

electrical potential can cause to move metal oxide or metal hydroxylation. Finally, the migration occurrence mechanism refers to results from the mass transfer induced by influencing factors, such as charge transfer in solution, diffusion and electrical migration.

(I) Anodic reaction

$$\begin{aligned} M &\rightarrow M^{n+} + ne^- \\ H_2O &\rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^- \\ M + H_2O &\rightarrow MO + 2H^+ + 2e^- \end{aligned} \tag{1}$$

(II) Cathodic reaction

$$\begin{aligned} M^{n+} + ne^- &\rightarrow M\downarrow \\ O_2 + 2H_2O + 4e^- &\rightarrow 4OH^- \\ 2H_2O + 2e^- &\rightarrow H_2 + 2OH^- \end{aligned} \tag{2}$$

(III) Inter-electrode reaction

$$\begin{aligned} M^{n+} + 2OH^- &\rightarrow M_nO\downarrow + H_2O \\ M^{n+} + 2OH^- &\rightarrow M_n(OH)_2\downarrow \end{aligned} \tag{3}$$

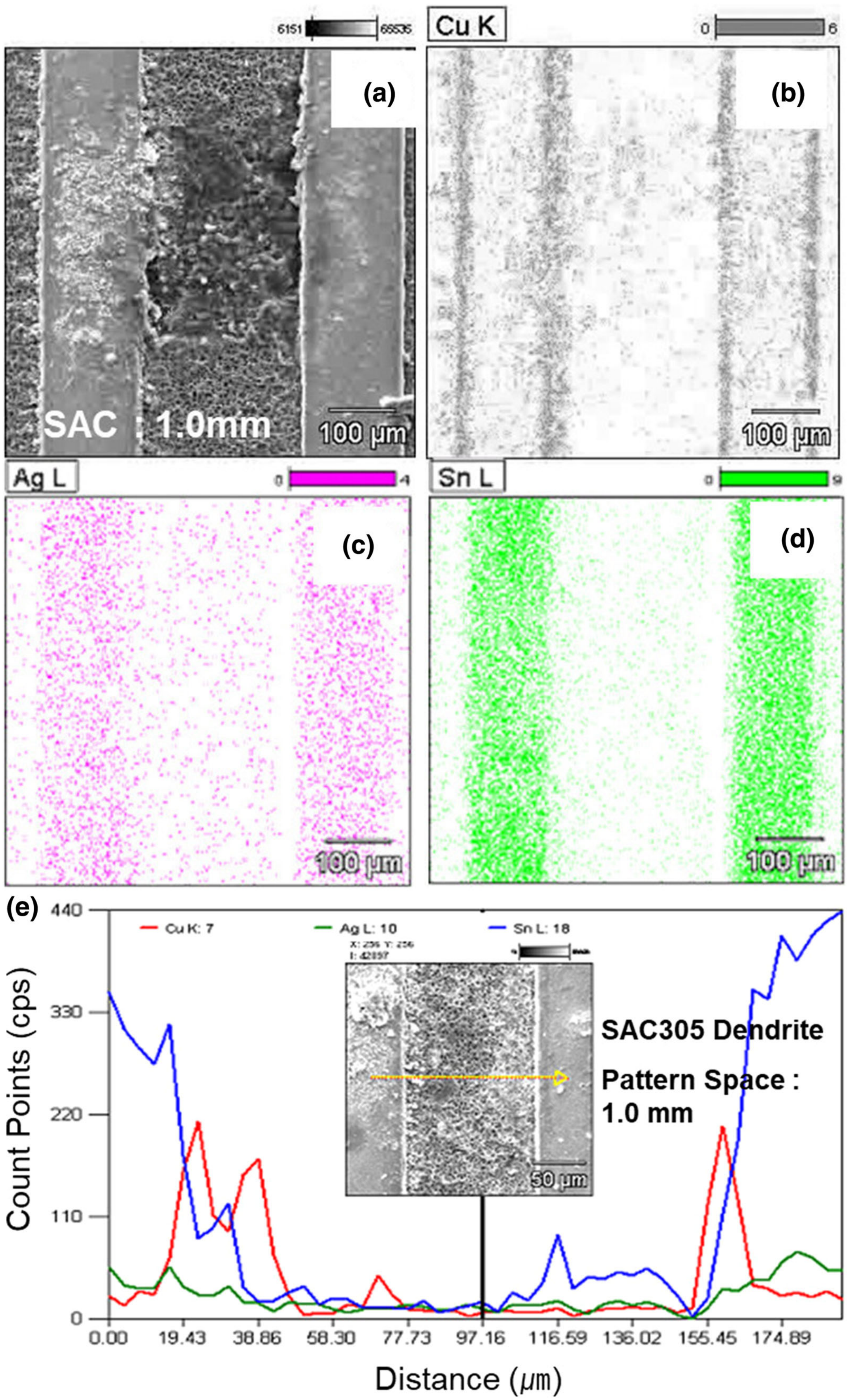

Fig. 5. (a) SEM images, (b–d) EDS mapping, and (e) line profile results with Cu, Ag, and Sn elements of dendrite in SAC305 conductor after THB test for 1000 h.

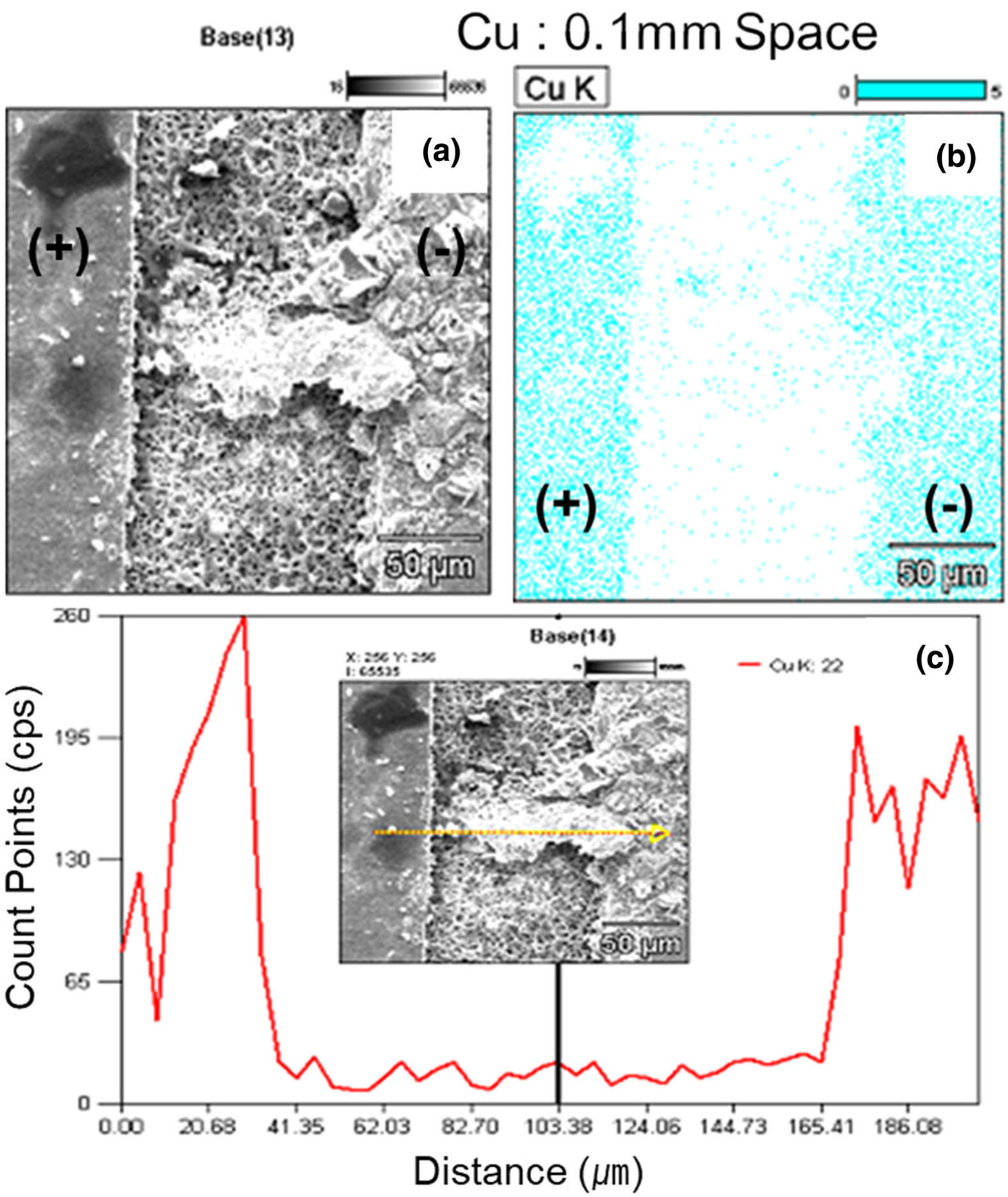

Fig. 6. (a) SEM images of Cu dendrite in Cu surface finish and (b) Cu EDS mapping results, and (c) Cu line profile results of dendrite after THB test for 1000 h.

Acceleration Lifetime Model for ECM

The Arrhenius model proposed by Hornung[18,19] is the most widely used model for chemical reaction rate behavior. Hornung's model is appropriate for estimating time-to-failure and acceleration factors, but it does not take into account relative humidity and bias voltage effects and is, therefore, not an appropriate ECM acceleration life model. Otherwise, the Eyring model expands upon the Arrhenius equation, adding terms for other stresses as necessary. This model is presented in the IPC 9201[7] for determination of the acceleration factors associated with this test. The Eyring model, as shown in Eq. 4, corrects the multiple stress and synergism problems of the Arrhenius model, but not without some drawbacks. The complexity of the Eyring model increases dramatically with every added ECM stress factor, as the number of unknowns increases twice as fast as the number of stresses. In addition, the stress functions are undefined. The stress could be a natural log, exponential, or some other function.[19] Where A is a scaling constant, E_a is activation energy (in eV), k is the Boltzmann constant (8.617×10^{-5} eV/K), T is temperature (K), α, B, C, D, E are constants determining stress interaction,

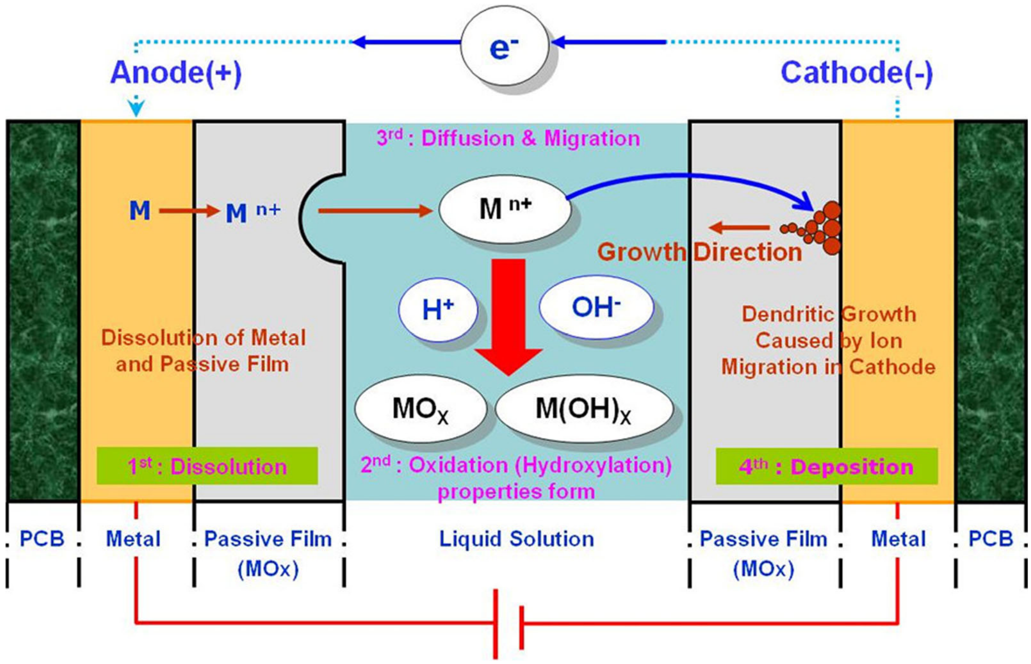

Fig. 7. Schematic diagram of electrochemical migration mechanism.

and S_1, S_2 and so on are stresses, such as humidity or voltage.

$$t_f = A \cdot T^{\alpha} \exp\left\{\frac{E_a}{kT} + \left(B + \frac{C}{T}\right)S_1 + \left(D + \frac{E}{T}\right)S_2 + A\right\} \quad (4)$$

If the ECM stresses were defined as bias voltage, relative humidity and temperature, the modified Eyring model, which is an acceleration model to predict the ECM life, can be expressed by Eq. 5. In this study, the modified Eyring model was used to predict the ECM time-to-failure in a use environment with the ENIG surface finish; in a 0.1 mm spacing of FR-4 PCB coated with solder mask under bias voltage; and in temperature- and humidity-related stresses that can be expressed by following Eq. 5. Where C is a constant, E_a is activation energy (in eV), R is the Boltzmann constant (8.617 × 10^{-5} eV/K), T is temperature (K), f is humidity factor, RH is relative humidity and V is bias voltage.

$$t_f = C \cdot \exp\left(\frac{-E_a}{RT}\right) \cdot \exp(f(\mathrm{RH})) \cdot V \quad (5)$$

Finally, the acceleration model to predict the ECM life Lfield, which is time-to-failure in use environment, can be expressed by Eq. 6:

$$L_{\mathrm{field}} = C \cdot \exp\left(\frac{E_a}{RT}\right) \cdot \exp(-f(\mathrm{RH})) \cdot V^{-1} \quad (6)$$

where L_{test} is the acceleration test duration for ECM assessment and can be calculated by Eq. 7, which is related to L_{field} which means expectation life in use environment.

Table III. Accelerated lifetime test results of electrochemical migration for obtaining humidity factor (*f*)

	ECM occurrence time (min)		
No.	**85°C, 75% RH**	**85°C, 85% RH**	**85°C, 95% RH**
1	1415	1077	1191
2	92,560	1989	1412
3	92,635	3267	1418
4	92,716	6228	5252
5	99,212	92,881	5610
6	100,016	93,252	10,247
7	No fail	94,278	21,354
8	No fail	133,153	37,615
9	No fail	143,529	95,974
10	no fail	No Fail	134,405

$$L_{\mathrm{test}} = \frac{L_{\mathrm{field}}}{\mathrm{AF}} \quad (7)$$

The acceleration factor (AF) for predicting ECM life means the ratio of fields and test conditions, and can be expressed by Eq. 8. If we know the activation energy and humidity factor, we can calculate AF and finally predict the ECM lifetime of the ENIG surface finish conductor. To obtain the AF, it is necessary to induce E_a and f. Where T_{field}, $\mathrm{RH}_{\mathrm{field}}$, and V_{field} is field condition, and T_{test}, $\mathrm{RH}_{\mathrm{test}}$, and V_{test} is acceleration test condition.

$$\mathrm{AF} = \exp\left(\frac{E_a}{R}\left(\frac{1}{T_{\mathrm{Field}}} - \frac{1}{T_{\mathrm{test}}}\right)\right) \cdot \exp(f(\mathrm{RH}_{\mathrm{test}} - \mathrm{RH}_{\mathrm{field}})) \cdot \frac{V_{\mathrm{test}}}{V_{\mathrm{field}}} \quad (8)$$

Table IV. Accelerated lifetime test results of electrochemical migration for obtaining activation energy (E_a)

	ECM occurrence time (min)		
No.	**85% RH, 65°C**	**85% RH, 75°C**	**85% RH, 85°C**
1	4875	5047	1077
2	6895	7895	1989
3	108,541	102,541	3267
4	132,541	135,852	6228
5	157,772	159,932	92,881
6	No Fail	No Fail	93,252
7	No Fail	No Fail	94,278
8	No Fail	No Fail	133,153
9	No Fail	No Fail	143,529
10	No Fail	No Fail	No Fail

ECM Lifetime Prediction

Tables III and IV show the ALT results of the ENIG surface finish for a 0.1 mm spacing in FR-4 PCB covered with a solder mask (modified epoxy acrylate) for inducing Ea and f using a THB test for 2666 h. We have conducted ALT until over 50% failure occurrence of all kinds of samples at each test condition. To calculate the humidity factor of Eq. 8, we conducted three types of THB tests at 85°C/75% RH, 85°C/85% RH and 85°C/95% RH. Using the same method to calculate the activation energy of Eq. 8, we have accomplished three types of THB tests at 65°C/85% RH, 75°C/85% RH and 85°C/85% RH.

From the optical microscope observation results (Fig. 8a and b), the dendrite was observed at the conductor spacing under the solder mask coating layer. Figure 8c shows the in situ monitoring result of insulation resistance variation due to ECM occurrence. In the continuous monitoring results, the insulation resistance dropped below 10^7 Ω and recovered to the initial resistance value instantly. This phenomenon is electrical breakdown caused by short circuit between the electrodes due to dendrite formation, and simultaneously we know that the

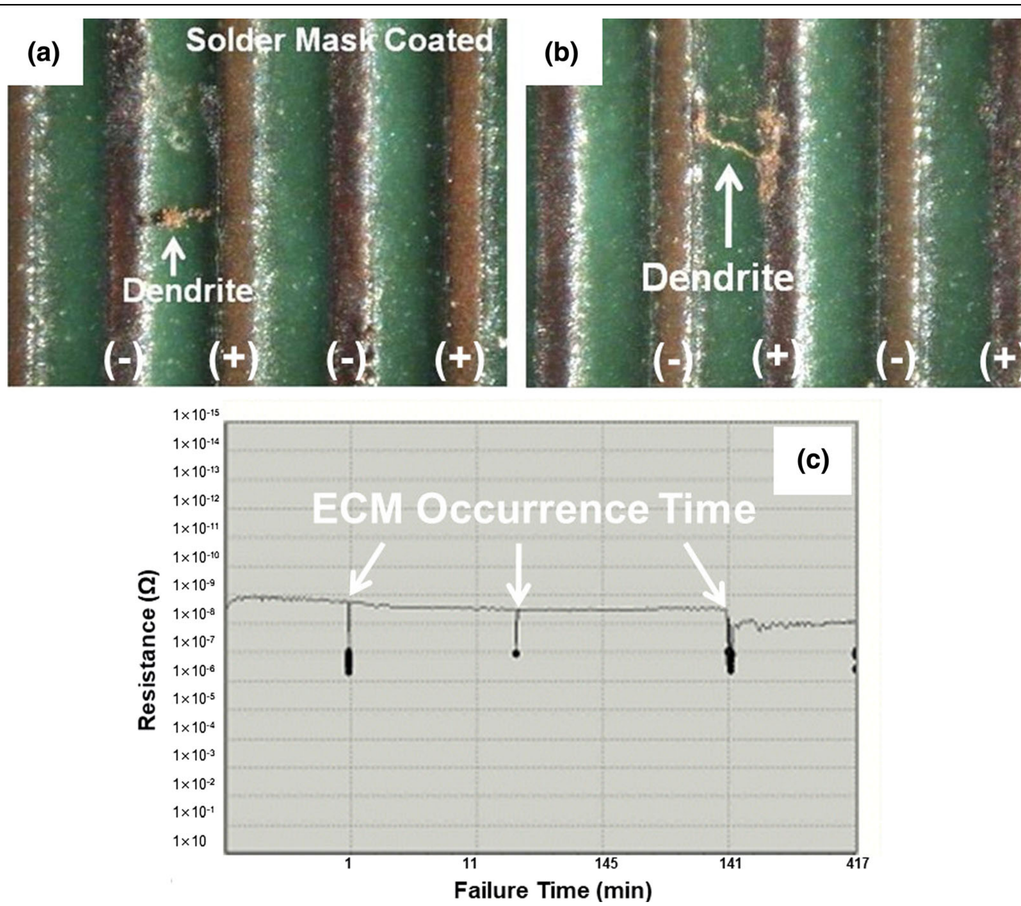

Fig. 8. (a) and (b) photographs of dendrite formation due to ECM occurrence, and (c) in situ monitoring result of insulation resistance variation due to ECM occurrence.

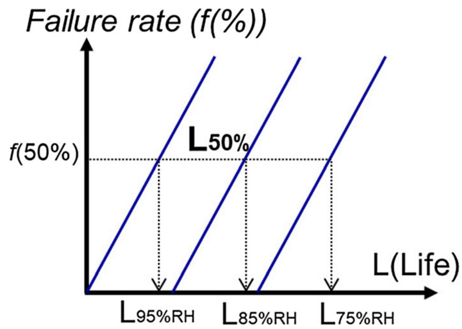

Fig. 9. Schematic graph for meaning of $L_{50\%}$, which means 50% cumulated failure rate at each THB test results.

Table V. Mean value of humidity factors

Humidity factors	Calculated values
f (75%/85%)	0.116
f (75%/95%)	0.118
f (85%/95%)	0.120
Mean value of humidity factor at $L_{50\%}$	0.118

Table VI. Mean value of activation energy

Activation energy	Calculated value (eV)
E (65°C/75°C)	0.004
E (65°C/85°C)	0.005
E (75°C/85°C)	0.006
Mean value of activation energy at $L_{50\%}$	0.005

insulation resistance was to be recovered due to dendrite breakdown after shortage.

From the ECM ALT results, the calculation method of E_a and f is as follows. The first, we have deduced to f. If we assume that the use temperature condition is equal to its test condition and the biased voltage is constant to 100 V, the humidity factor (f) from Eq. 8 can be expressed by Eq. 9:

$$K = \exp(f \cdot \mathrm{RH}) \tag{9}$$

To obtain the f value for the humidity effect, AF can be obtained from the ECM life ratio of 75% RH and 85% RH humidity conditions, as shown in Eq. 10. Figure 9 gives an explanation of the calculation method of mean values, where L means 50% cumulated ECM failure rate obtained from three types of THB test results. Using the same calculation method, we can obtain the three kinds of f values of 0.116, 0.118 and 0.120, as shown in Table V. Consequently, the humidity factor is 0.118, which is the mean value at $L_{50\%}$.

$$\begin{aligned} L_{75\%} &= C_2 \times \exp(f \times \mathrm{RH}_{75}) \\ L_{85\%} &= C_2 \times \exp(f \times \mathrm{RH}_{85}) \\ \frac{L_{75\%}}{L_{85\%}} &= \exp(f \times (\mathrm{RH}_{85\%} - \mathrm{RH}_{75\%})) \\ f_{75\%/85\%} &= \ln\left(\frac{L_{75\%}}{L_{85\%}}\right) \times \left(\frac{1}{\mathrm{RH}_{85\%} - \mathrm{RH}_{75\%}}\right) \end{aligned} \tag{10}$$

In the same way to calculate f value, we can estimate the E_a value. If the humidity is constant based on Eq. 8, E_a for reflecting the temperature affecting on ECM can be induced to use the Arrhenius model.

$$\begin{aligned} K = C_1 \cdot \exp\left(\frac{-E_a}{RT}\right) &\Rightarrow \ln K = \ln C_1 - \frac{E_a}{RT} \\ &\Rightarrow \ln L = \ln C_2 + \frac{E_a}{RT} \end{aligned} \tag{11}$$

Assuming the use humidity condition and its test condition are equal, E_a can be expressed to Eq. 12. Where, if the applied voltage is 100 V and AF for temperature is given by Eq. 12.

$$\mathrm{AF} = \exp\left(\frac{E_a}{R}\left(\frac{1}{T_{\mathrm{Field}}} - \frac{1}{T_{\mathrm{test}}}\right)\right) \tag{12}$$

Because AF means the ratio of field life and test life, Eq. 12 can be transformed to Eq. 13. If we know the ratio of life, L_1/L_2, we can calculate E_a from Eq. 13.

$$\begin{aligned} \mathrm{AF} = \frac{L_1}{L_2} &= \exp\left(\frac{E_a}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right) \\ \Rightarrow E_a &= \ln\left(\frac{L_1}{L_2}\right) \cdot R\left(\frac{T_1 T_2}{T_2 - T_1}\right) \end{aligned} \tag{13}$$

Table VI shows the three kinds of E_a value, 0.004, 0.005 and 0.006, obtained from three types of THB test results. Finally, 0.005 is the mean value of E_a and is utilized to predict the ECM life of FR-4 PCB with the ENIG surface finish. If we substitute these results (E_a is 0.005 and f is 0.118) for Eq. 8, the acceleration model for AF is expressed by Eq. 14. Supposing that the use condition is 25°C, 50% RH and bias voltage is 5 V, AF can be obtained to 1286 under 85°C and 85% RH test conditions.

$$\begin{aligned} \mathrm{AF} &= \exp\left(\frac{0.005}{0.000083}\left(\frac{1}{298} - \frac{1}{358}\right)\right) \\ &\quad \cdot \exp(0.118(85 - 50)) \cdot \frac{100}{5} \\ &= 1286 \end{aligned} \tag{14}$$

If we assume to use 8 h per day under 25°C, 50% RH and 5 V as use conditions which is general interior use condition of electronics, we know that

B_{10} life for ECM to occur in use environment can be induced to be 15 years (43,800 h).

CONCLUSIONS

We have validated the stress factors for ECM to occur through THB testing. In addition, we introduced an acceleration model and acceleration factor for predicting the ECM life considered to temperature, humidity and bias voltage stresses and finally, we obtained the following results.

From THB test results, we know that the stress factors for ECM occurrence are temperature, humidity, surface finish materials, spacing and bias voltage and that the THB test is a very efficient method to compare with each stress factor. Through in situ monitoring of SIR, and SEM and EDS mapping between the conductors, the dendrite formation was directly observed.

Furthermore, we have defined the modified Eyring model as an accelerated life prediction model for ECM to occur. To predict the ECM life, we have conducted to the ALT. Consequently, we have obtained that the activation energy (0.005) and humidity factor (0.118), and then the AF was calculated to be 1286 under 85°C, 85% RH and 100 V test condition. This AF can be applicable in FR-4 PCB with an ENIG surface finish covered with a solder mask under temperature, humidity and voltage stress factors. If we assumed to use 8 h per day under 25°C, 50% RH and 5 V as use conditions, we have known that B_{10} life for ECM to occur in use environment can be predicted to be 15 years.

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