Derivation of Electromigration Characteristic Constants of Metal Line Used in Electronic Devices

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Abstract

Divergence of atomic flux due to electromigration has been formulated for Al polycrystalline line covered with a passivation layer. The formula has been identified as a governing parameter for electromigration damage in the line through experimental verification. It is known that local depletion of atoms, i.e. void appears in metal line used in electronic devices as a result of electromigration. So far, the velocity of depletion of atoms was expressed using the parameter to construct a derivation method for characteristic constants of electromigration damage in Al line. In this study, the electromigration characteristic constants of typical Cu line used in electronic devices are derived based on the derivation method for Al line. Through the discussion about the validity of the obtained constants, it is shown that the parameter-based method can determine the electromigration characteristic constants appropriately.

1 Introduction

The fine Cu lines in printed circuit board (PCB) of electronic devices are recently stressed by high-density electric current. Electromigration damage is getting to be recognized as one of the major reliability concern in printed circuit, as well as Cu lines in silicon integrated circuits (ICs). Electromigration is the transportation of metallic atoms by electron wind. The divergence of atomic flux due to electromigration causes a degradation of the metal line, formation of voids and hillocks, and subsequent line failure.

In Al polycrystalline line in silicon IC, it can be assumed that the grain boundary diffusion by electromigration is dominant. Based on the assumptions, the divergence of atomic flux due to electromigration has been formulated for the polycrystalline line covered with a passivation layer. The formula has been identified as a governing parameter for electromigration damage in passivated polycrystalline line, AFD^{*}_{gen}, through experimental verification [1]. Using the governing parameter, a numerical simulation method has been developed to predict the line failure [2]. By the way, it is known that local depletion of atoms, i.e. void appears in Al lines as a result of electromigration. So far, the velocity of depletion of atoms was expressed using the parameter to construct a derivation method for electromigration characteristics of the silicon IC line. The validity of the derivation method was shown by experiment [1]. However, the derivation method of electromigration characteristics has not yet been developed for Cu lines in PCB.

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In this study, we try applying the derivation method for Al lines in silicon IC to Cu lines in PCB, as the first step in development of the evaluation method for electromigration reliability. The electromigration characteristic constants are determined based on the measurement of the speed of void growth. Through the discussion on the validity of the obtained constants, it is discussed whether the parameter-based derivation method can appropriately determine the electromigration characteristic constants of Cu line in PCB.

2 Governing Parameter for Electromigration Damage

The governing parameter for electromigration damage in Al lines of silicon IC has been formulated based on the atomic flux formula expressed by [1]

$$|\mathbf{J}| = \frac{ND_0}{kT}\exp\left\{-\frac{Q_{gb}+\kappa\Omega(N-N_T)/N_0-\sigma_T\Omega}{kT}\right\}\left(Z^*e\rho j^* - \frac{\kappa\Omega}{N_0}\frac{\partial N}{\partial l}\right) \tag{1}$$

where $\mathbf{J}$ is atomic flux vector, N atomic density, D_0 a prefactor, k Boltzmann's constant, T absolute temperature, Q_{gb} is the activation energy for grain boundary diffusion, κ the constant relating the change in mechanical stress with the change in atomic density under restriction by passivation, Ω atomic volume, N_T the atomic density under tensile thermal stress σ_T, N_0 the atomic density under stress-free condition, Z^* effective valence, e electronic charge, $\rho\ [=\rho_0\{1+\alpha(T-T_s)\}]$ temperature-dependent resistivity, ρ_0 and α the electrical resistivity and the temperature coefficient at the substrate temperature T_s. Symbols j^* and $\partial N/\partial l$ are the components of the current density vector and the atomic density gradient in the direction of $\mathbf{J}$, respectively. In the equation, the back flow due to the stress gradient and the effect of the stress on diffusivity are taken into account. Lattice diffusion can be neglected in the case of electromigration in Al polycrystalline line because the main diffusion path of atoms is along the grain boundary [3].

Introducing a model of the polycrystalline microstructure [4], the divergence of the atomic flux was formulated [1]. If we assume that the angle between a microstructure unit [4] and the x-axis is θ, then the rate of decrease of atoms per unit volume, denoted as $AFD^*_{gb\theta}$, is given by

$$\begin{aligned}
AFD^*_{gb\theta} = {} & C^*_{gb} N \frac{4}{\sqrt{3}d^2}\frac{1}{T}\exp\left\{-\frac{Q_{gb}+\kappa\Omega(N-N_T)/N_0-\sigma_T\Omega}{kT}\right\}\times \\
& \Bigg\langle \sqrt{3}\Delta\varphi\left\{(j_x\cos\theta + j_y\sin\theta)Z^*e\rho - \frac{\kappa\Omega}{N_0}\left(\frac{\partial N}{\partial x}\cos\theta+\frac{\partial N}{\partial y}\sin\theta\right)\right\} \\
& -\frac{d}{2}\Delta\varphi\left\{\left(\frac{\partial j_x}{\partial x}-\frac{\partial j_y}{\partial y}\right)Z^*e\rho\cos 2\theta - \frac{\kappa\Omega}{N_0}\left(\frac{\partial^2 N}{\partial x^2}-\frac{\partial^2 N}{\partial y^2}\right)\cos 2\theta + \left(\frac{\partial j_x}{\partial y}+\frac{\partial j_y}{\partial x}\right)Z^*e\rho\sin 2\theta - 2\frac{\kappa\Omega}{N_0}\frac{\partial^2 N}{\partial x\partial y}\sin 2\theta\right\} \\
& -\frac{\sqrt{3}}{4}d\frac{\kappa\Omega}{N_0}\left(\frac{\partial^2 N}{\partial x^2}+\frac{\partial^2 N}{\partial y^2}\right) - \frac{\kappa\Omega/N_0}{kT}\left[\frac{\sqrt{3}}{4}d\left\{Z^*e\rho\left(j_x\frac{\partial N}{\partial x}+j_y\frac{\partial N}{\partial y}\right)-\frac{\kappa\Omega}{N_0}\left(\frac{\partial N}{\partial x}\frac{\partial N}{\partial x}+\frac{\partial N}{\partial y}\frac{\partial N}{\partial y}\right)\right\}\right. \\
& \left. -\frac{d}{2}\Delta\varphi\left\{Z^*e\rho\left(j_x\frac{\partial N}{\partial x}+j_y\frac{\partial N}{\partial y}\right)-2\frac{\kappa\Omega}{N_0}\frac{\partial N}{\partial x}\frac{\partial N}{\partial y}\right\}\sin 2\theta\right] \\
& +\frac{\sqrt{3}d}{4T}\left\{\frac{Q_{gb}+\kappa\Omega(N-N_T)/N_0-\sigma_T\Omega}{kT}-1\right\}\left\{Z^*e\rho\left(j_x\frac{\partial T}{\partial x}+j_y\frac{\partial T}{\partial y}\right)-\frac{\kappa\Omega}{N_0}\left(\frac{\partial N}{\partial x}\frac{\partial T}{\partial x}+\frac{\partial N}{\partial y}\frac{\partial T}{\partial y}\right)\right\}\Bigg\rangle
\end{aligned} \tag{2}$$

where $C^*_{gb} = \delta D_0/k$, the first term in the angle brackets on the right-hand side of Eq. (2) is related to the atomic flux divergence at a triple point of grain boundaries, and the other terms are related to the flux divergence in a grain boundary itself. When $AFD^*_{gb\theta}$ takes a positive value, then we have the case of depletion of atoms. On the other hand, when $AFD^*_{gb\theta}$ takes a negative value, then atoms will be accumulated. The angle θ takes an arbitrary value in practice. One needs to consider the flux divergence in the whole range of θ, i.e., from 0 to 2π. Taking notice of the atomic flux divergence contributing to the formation of void, the expected value of only positive values of $AFD^*_{gb\theta}$ for $0 \le \theta \le 2\pi$ is calculated. Thus, the atomic flux divergence, AFD^*_{gen}, concerning void formation in polycrystalline line is derived as

$$AFD^*_{gen} = \frac{1}{4\pi}\int_0^{2\pi}\left(AFD^*_{gb\theta} + \left|AFD^*_{gb\theta}\right|\right)d\theta \tag{3}$$

where the atomic flux divergence due to the lattice diffusion is neglected considering application to Al polycrystalline line.

3 Derivation Method of Film Characteristic Constants

The film characteristic constants included in the formula of AFD^*_{gen} are d, Q_{gb}, $\Delta\varphi$, Z^*, C^*_{gb} and κ. The AFD^*_{gen} - based method for determination of these characteristics has been derived, treating the center region of a straight line in which current density and temperature can be regarded as being constant [1]. First, let N be approximately equal to N_0 because it is assumed that the change in N from N_0 is enough small considering the magnitude of stress in the metal line. The average grain size, d, can be measured using focused ion beam (FIB) equipment or scanning electron microscopy (SEM). As far as $\Delta\varphi$ is concerned the value is obtained from an un-covered metal line made of Al film [1]. During the initial stage of electromigration damage, the atomic density gradient is assumed to be linear within the center region of the line. The product $\kappa\cdot\partial N/\partial x$ is determined as a characteristic which depends on the line-length of the straight line and the passivation material used.

The film characteristics $Q^*_{gb}[=Q_{gb}-\sigma_T\Omega]$, Z^*, C^*_{gb} and $\kappa\cdot\partial N/\partial x$ are determined experimentally using the straight shaped test line as follows. Accelerated tests are performed for a certain period of time. The straight line is subjected to input current density, j_1, under three different atmospheric temperatures in oven, T_{a1}, T_{a2} and T_{a3}. Then, let the temperature in the center region of the line under electric current flow be T_1, T_2 and T_3 in the cases when the atmospheric temperature in oven is T_{a1}, T_{a2} and T_{a3}, respectively. Let us denote each experimental condition as Condition-1: j_1 and T_1, Condition-2: j_1 and T_2, and Condition-3: j_1 and T_3, respectively. In addition to these conditions, the acceleration test is also performed under a current density j_4, different from j_1. Under this condition, the atmospheric temperature in oven is controlled so that the temperature T_4 in the center region of the line is approximately equal to T_3. Let us call this experimental condition Condition-4: j_4 and $T_4(\cong T_3)$. The void volume is measured within the center region of the line after current stressing for a certain period of time.

On the other hand, considering the center region of the straight line, the formula of AFD^*_{gen} is simplified by neglecting the terms associated with the temperature gradient, the current density gradient and the gradient of atomic density gradient. The simplified AFD^*_{gen} is multiplied by the area of the center region, the line thickness, the net current-applying time and the atomic volume, to theoretically obtain the void volume. By equating the theoretical void volume with the void volume obtained experimentally, we get the following equation:

$$V_j = A \times t_j \times thick \times \frac{4}{\sqrt{3}d^2} \times \frac{C^*_{gb}}{T_j} \exp\left(-\frac{Q^*_{gb}}{kT_j}\right)\left(Z^* e\rho_j j_j - \frac{\Omega}{N_0}\kappa\frac{\partial N}{\partial x}\right) \times \frac{\sqrt{3}\Delta\varphi}{\pi}\left\{\sqrt{1-\left(\frac{a_j}{b}\kappa\frac{\partial N}{\partial x}\right)^2} - \frac{a_j}{b}\kappa\frac{\partial N}{\partial x}\cos^{-1}\left(\frac{a_j}{b}\kappa\frac{\partial N}{\partial x}\right)\right\}, \tag{4}$$

where

$$a_j = \frac{\sqrt{3}}{4}\frac{\Omega/N_0}{kT_j}d \ , \tag{5}$$

$$b = \sqrt{3}\Delta\varphi \quad , \tag{6}$$

subscript j represents the number of each condition, V_j is the measured void volume, A is the area of the center region, t_j is the net current-applying time, *thick* is the line-thickness and ρ_j is the resistivity of the line at T_j. The unknown film characteristics in AFD^*_{gen} can be obtained using the least-squares method. Namely, the characteristics are determined so that the following sum takes a minimum value:

$$F = \sum_j \sum_i \left[\ln V_{ij} - \ln\left\langle A \times t_{ij} \times thick \times \frac{4}{\sqrt{3}d^2} \times \frac{C^*_{gb}}{T_j}\exp\left(-\frac{Q^*_{gb}}{kT_j}\right)\left(Z^* e\rho_j j_j - \frac{\Omega}{N_0}\kappa\frac{\partial N}{\partial x}\right) \times \frac{\sqrt{3}\Delta\varphi}{\pi}\left\{\sqrt{1-\left(\frac{a_j}{b}\kappa\frac{\partial N}{\partial x}\right)^2} - \frac{a_j}{b}\kappa\frac{\partial N}{\partial x}\cos^{-1}\left(\frac{a_j}{b}\kappa\frac{\partial N}{\partial x}\right)\right\}\right\rangle\right]^2 \tag{7}$$

where subscript i represents the number of data measured in each experimental condition. By this method, the film characteristics can be obtained as the optimized parameters which approximate all experimental data.

4 Application of the AFD^*_{gen}-Based Method for Determination of Film Characteristics

4.1 Experiment

The Cu straight line specimens were fabricated as follows. The Cu layer of commercial copper-clad laminate for flexible printed circuits was chemically etched to fabricate line shape. The thickness of polyimide base film was 40 μm, and that of Cu layer was 8 μm, respectively. Next, the specimen was covered with solder resist expect current input/output pads. The thickness of solder resist was 8 μm. Finally, small pieces of polyimide and Al film tape were affixed to the test line part for promoting heat dissipation. The thicknesses of both polyimide and Al film tape were 60 μm. The line length was 100 μm and the line width was 10 μm. The dimensions of the Cu line specimen are shown in Fig. 1.

The accelerated tests were performed to measure the void volume. The change in electrical potential drop in the line was monitored. The three different atmospheric temperatures, 323, 333 and 343 K, were selected. For each temperature, the metal lines were subjected to direct current with density of 2.52 MA/cm^2 (Condition-1, -2 and -3). In addition, the test was performed under a current density of 2.27 MA/cm^2 and the atmospheric temperature of 343 K (Condition-4). Eight specimens were used under condition-1, nine specimens were used under condition-2 and 3, and ten specimens were used under condition-4. An electric current was supplied until 10 % increase in potential drop. After that, the solder resist layer was removed by reactive ion etching (RIE). The specimen's surface was scraped away by flat milling equipment and then Cu lines were observed by using scanning electron microscopy (SEM).

The specimen not stressed by electric current and the specimen after current stressing were observed for comparing as shown in Fig. 2. The observed area of the center region for void measuring was set at a rectangle 30 μm in length along the longitudinal axis and 10 μm in width. From observation of specimen without current supply, it was shown that Cu line was intact without void, and from observation of specimen with current supply it was found that voids were formed at the triple point of grain boundaries, and grain boundary diffusion due to electromigration was dominant. Total area of the voids formed within the observed region was summed up by image-processing of the SEM image, and the volume of the voids was inferred by multiplying the Cu film thickness to the total area of the voids as the first approximation. The current-applying time was different for each specimen and each experimental condition because current stressing was stopped when 10 % increase in potential drop. Temperatures in the specimens under current supply were inferred based on temperature dependency of electric resistance of the specimen, by measuring increment of potential drop under constant current.

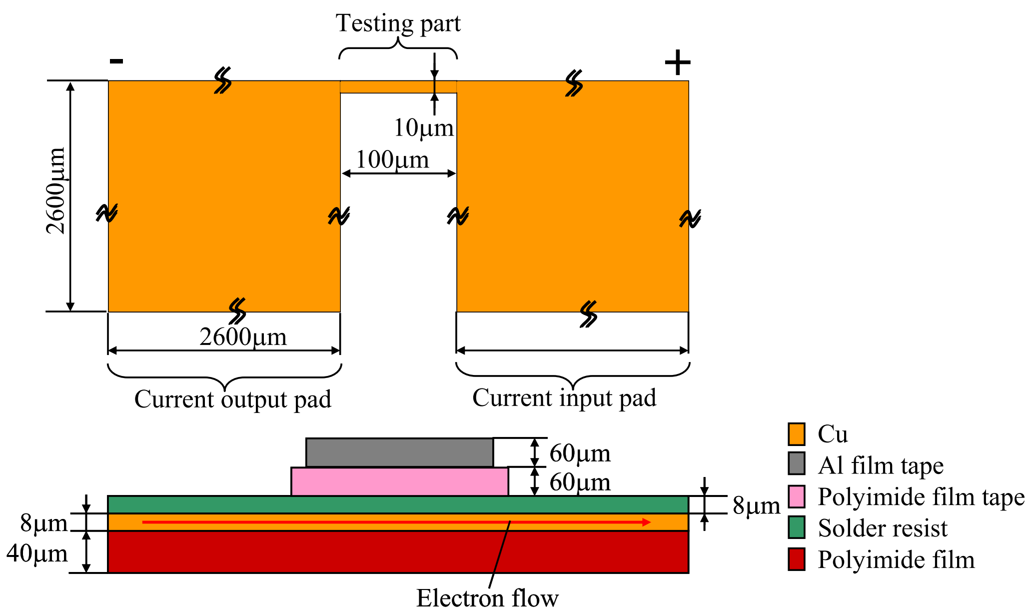
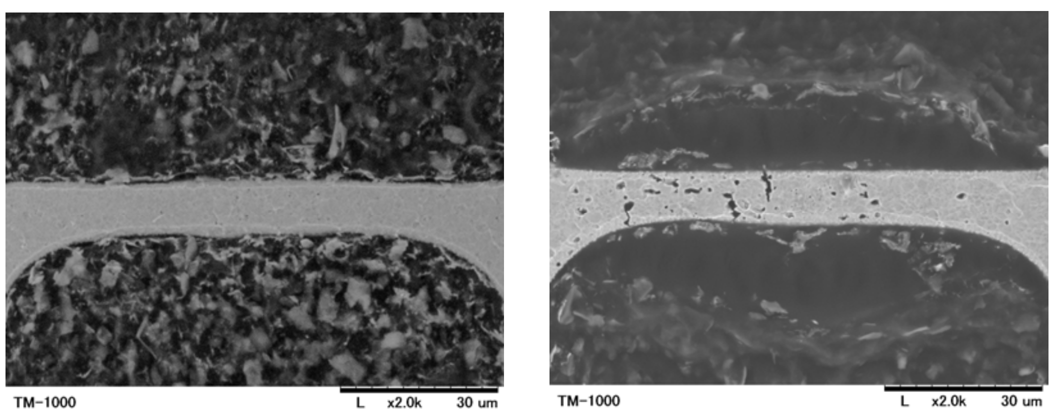


Fig. 1 Dimensions of the copper line specimen used in experiment

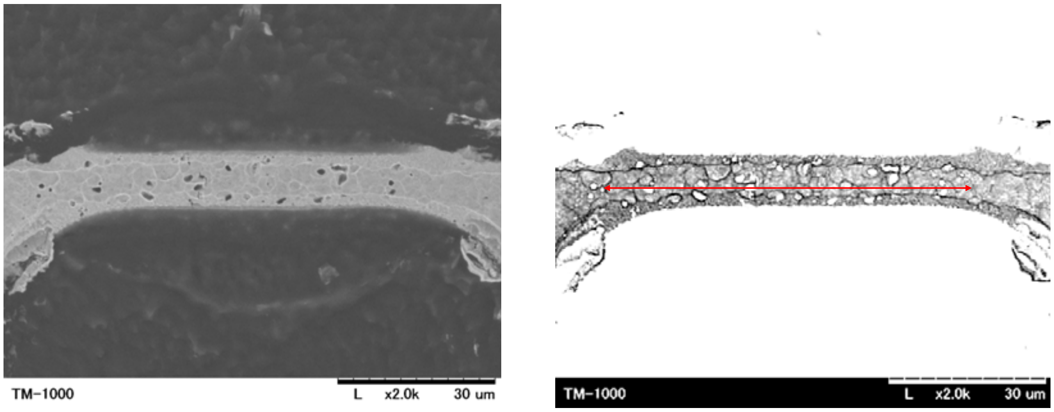


(a) Without current supply (b) With current supply

Fig. 2 SEM Observations of lines without and with current supplying

4.2 Optimization of film characteristic constants

The parameter AFD^{*}_{gen}-based method for electromigration characteristic derivation was applied to the Cu lines in flexible printed circuits by using the experimental data obtained, although the method is based on the assumption of 2-dimensional microstructure and perhaps there are plural grains in Cu line thickness. In this study, the average grain size was measured based on the SEM image after enhancement of outline of crystal grains as shown in Fig. 3. The quantity of $\Delta\varphi$, -0.0314 rad, which was obtained as that in Al line [5], was used. The quantities Ω, ρ_0 and α for Cu were cited from literatures [6]. The film characteristics were obtained by the optimization based on least-squares method as listed in Table 1.



(a) SEM image of test line (b) Enhacement of outlines of crystal grains in SEM image

Fig. 3 SEM images of test line to measure the average grain size

Table 1 The film characteristics included in AFD^*_{gen}

Q^*_{gb} [eV]	Z^*	C^*_{gb} [Kμm^3/Js]	$\kappa(\partial N/\partial x)$[J/$\mu$m^7]
0.964	-0.388	6.44×10^{31}	-0.211

4.3 Discussion

The values, 0.964 eV, was obtained as the activation energy. The values of Q^*_{gb} obtained in this study was close to that for Cu diffusion along grain boundaries reported by Tu [7], although it was a bit smaller. On the other hand, the values of Z^* obtained was almost the same as the previously reported values, -0.4±0.12 (Wei, et al [8]).

The following function, G^*, can be defined by arranging the logarithm of both sides in Eq. (4):

$$G^* = \ln\left[\frac{V_{ij}T_j}{\dfrac{4\times A\times t_{ij}\times thick\times C^*_{gb}\times\Delta\varphi}{\pi d^2}\left(Z^*e\rho_j j_j-\dfrac{\Omega}{N_0}\kappa\dfrac{\partial N}{\partial x}\right)\left\{\sqrt{1-\left(\dfrac{a_j}{b}\kappa\dfrac{\partial N}{\partial x}\right)^2}-\dfrac{a_j}{b}\kappa\dfrac{\partial N}{\partial x}\cos^{-1}\left(\dfrac{a_j}{b}\kappa\dfrac{\partial N}{\partial x}\right)\right\}}\right]. \tag{8}$$

The film characteristic constants obtained were substituted into G^* and it was plotted against $1/T$ as shown in Fig. 4, where T is the inferred temperature of specimen. The figure shows one linear relation, and its slope means $-Q^*_{gb}/k$. It, accordingly, was realized that the least-squares method functioned effectively and approximated well the experimental data. Furthermore, the correlation coefficient was -0.71.

From the validity of the obtained constants, it was shown that the AFD^{*}_{gen}-based method was able to reflect the atomic diffusion mechanism appropriately and to determine the film characteristics accurately for Cu line in PCB.

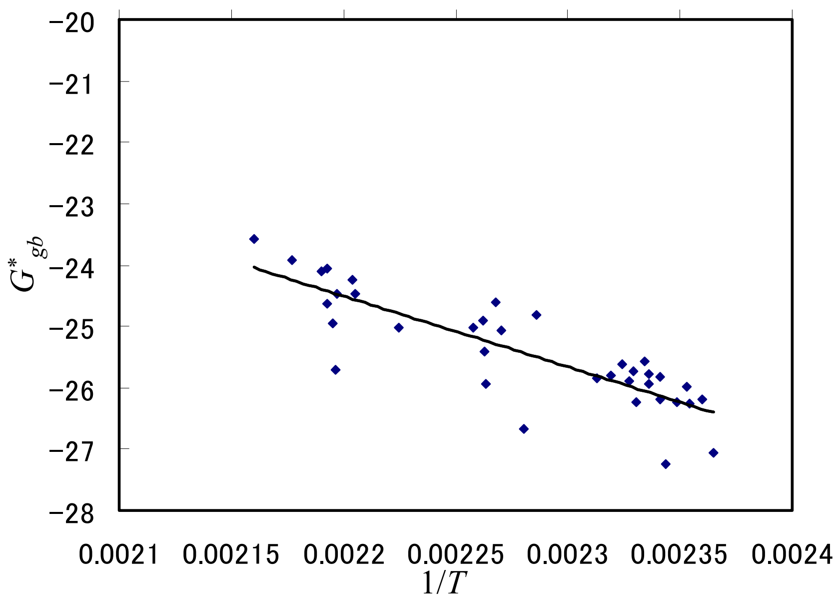


Fig. 4 Approximation by the least-squares method when applying the AFD^{*}_{gen}-based method to Cu line in PCB

5 Conclusions

The derivation method for film characteristics for Al lines in silicon IC was applied to Cu line in PCB. The film characteristics were obtained by using least-squares method for the void growth data experimentally obtained. The values of activation energy for Cu atomic diffusion and effective valance for electromigration were found to be valid in comparison with values in previous literatures. It was shown that the AFD^{*}_{gen}-based method was able to reflect the atomic diffusion mechanism appropriately and to determine the film characteristics accurately for the Cu line in PCB.

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