DERIVATION OF FILM CHRACTERISTIC CONSTANTS BY USING GOVERNING PARAMETER FOR ELECTROMIGRATION DAMAGE IN PASSIVATED BAMBOO LINE

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ABSTRACT

The governing parameter for electromigration damage in the passivated bamboo lines, called AFD^*_{li}, was recently formulated by considering the divergence of atomic flux due to electromigration. The formulation was based on the parameter AFD_{li} previously introduced in our studies. The parameter AFD_{li} has been identified as the governing parameter for electromigration damage in unpassivated bamboo lines through experimental verification process. On the other hand, metal lines used in integrated-circuit (IC) products are covered with passivation or dielectric layer. A mechanical stress (atomic density) distribution induced by electromigration appears in such lines and plays an important role in the electromigration mechanism. The parameter, AFD^*_{li} , was formulated by adding the effect of the atomic density gradient to AFD_{li}. By the way, it is known that the displacement of line edge appears at the cathode end of via-connected line as a result of electromigration. So far, the velocity of the edge displacement, the so-called drift velocity, was expressed by using AFD^*_{li} to construct an AFD^*_{li}-based method for determination of film characteristics. In this study, the film characteristic constants in AFD^*_{li} are experimentally determined from the measurement of the drift velocity, where two kinds of metal lines with different line-lengths are treated. Some of the unknown film characteristics do not depend on the line-length and others depend on the length. The film characteristic constants included in AFD^*_{li} are obtained for two metal lines so that the drift velocity calculated by AFD^*_{li} agrees with measured one. Through the discussion on the validity of the obtained constants, it is shown that the AFD^*_{li}-based method can determine both the film characteristics independent of the line-length and another constant depending on the line-length appropriately.

1 INTRODUCTION

The fine metal lines in IC are stressed by high-density electric current. Electromigration damage has been recognized as one of the major reliability concern in IC. 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, that is, formation of void and hillock.

The semiconductor industry is characterized by the trend toward the integration of IC. As the line-width becomes finer with the same chip size, the grain microstructure of the line becomes bamboo-like. In the bamboo line, there are a few grain boundaries and these are perpendicular to the longitudinal axis of the line. So, it can be assumed that the atomic flux divergence in the grain boundary is negligible (Vaidya et al.[1]), and that the lattice diffusion including interface diffusion by electromigration is dominant in the bamboo line (Oates[2] and Proost et al.[3]). Based on the assumptions, the atomic flux divergence due to electromigration in the unpassivated bamboo line, AFD_{li}, was formulated by Sasagawa et al.[4]. On the other hand, the metal lines in IC products are covered with passivation or dielectric layer. In the covered metal line a mechanical stress (atomic density) distribution is induced by electromigration. The gradient of the atomic density plays an important role in the mechanism of electromigration damage in passivated metal line and is inversely proportion to line-length, as shown by Blech[5]. The atomic diffusion in the opposite direction to atomic flow due to electromigration, the so-called back flow, is induced by the atomic density gradient. So far, a governing parameter for electromigration damage in the passivated bamboo line, AFD^*_{li}, was proposed by Hasegawa[6]. The parameter AFD^*_{li} was formulated by adding the effect of atomic density gradient to AFD_{li}.

By the way, the metal lines in IC are often connected with vias to construct a multi-level structure. In the metal line with via, no atoms are supplied to the cathode end of line by electromigration because the atomic flow is intercepted by the vias made of tungsten and so on. Therefore, the metal line connected with via has the failure mode that the cathode edge of the line drifts in the direction of electron flow. Recently, the velocity of the drift was theoretically expressed using AFD^*_{li} and a method to determine the film characteristic constants in AFD^*_{li} was also presented by utilizing the measurement of the drift velocity (Hasegawa[6]). In AFD^*_{li}-based method, the film characteristic constants included in AFD^*_{li} are obtained so that the drift velocity calculated by AFD^*_{li} agrees with measured one.

In this study, accelerated tests to measure the drift velocity are conducted by using the specimen supposing the via-connected line, where two kinds of metal lines with different line-lengths are treated. By applying the AFD^*_{li}-based method to these lines, the film characteristic constants are determined for two metal lines. Some of the unknown film characteristics must be dependent on the line-length and others must be independent of the length. Through the discussion on the validity of the obtained film characteristic constants, it is shown that the film characteristic constants can be determined appropriately by the AFD^*_{li}-based method.

2 GOVERNING PARAMETER FOR ELECTROMIGRATION DAMAGE

The governing parameter was formulated based on the atomic flux formula expressed by

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

where $\boldsymbol{J}$ is atomic flux vector, N atomic density, D_0 a prefactor, k Boltzmann's constant, T absolute temperature, Q_{li} net activation energy for bamboo line which may include both the lattice and the interface diffusion mechanisms, κ the constant relating the change in 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 $\boldsymbol{J}$, respectively. In the equation, the back flow due to the stress gradient and the effect of the stress on diffusivity are taken into account. It is also assumed that, in the bamboo line, the atomic flux divergence in the grain boundary is negligible and that the lattice diffusion including interface diffusion by electromigration is dominant. The motivation behind this assumption is that there are a few grain boundaries and these are perpendicular to the longitudinal axis of the line. So, we can consider the direction of $\boldsymbol{J}$ agrees with that of current density vector $\boldsymbol{j}$. Based on eqn (1), the atomic flux divergence by electromigration, AFD^*_{li}, in the passivated bamboo line was given by

$$\begin{aligned}
AFD^*_{li} &= \mathrm{div}\boldsymbol{J} = \frac{C^*_{li}N}{T}\exp\left(-\frac{Q_{li}+\kappa\Omega(N-N_T)/N_0-\sigma_T\Omega}{kT}\right)\\
&\times\left[\frac{1}{T}\left(\frac{Q_{li}+\kappa\Omega(N-N_T)/N_0-\sigma_T\Omega}{kT}-1\right)\left\{Z^*e\rho\left(j_x\frac{\partial T}{\partial x}+j_y\frac{\partial T}{\partial y}\right)-\frac{\kappa\Omega}{N_0}\left(\frac{\partial N}{\partial x}\frac{\partial T}{\partial x}+\frac{\partial N}{\partial y}\frac{\partial T}{\partial y}\right)\right\}\right.\\
&\left.-\frac{\kappa\Omega/N_0}{kT}\left\{Z^*e\rho\left(j_x\frac{\partial N}{\partial x}+j_y\frac{\partial N}{\partial y}\right)-\frac{\kappa\Omega}{N_0}\left(\frac{\partial N}{\partial x}\frac{\partial N}{\partial x}+\frac{\partial N}{\partial y}\frac{\partial N}{\partial y}\right)\right\}-\frac{\kappa\Omega}{N_0}\left(\frac{\partial^2 N}{\partial x^2}+\frac{\partial^2 N}{\partial y^2}\right)\right]
\end{aligned} \tag{2}$$

where $C^*_{li}=D_0/k$, and AFD^*_{li} expresses the amount of the flux divergence within the grain and in the interface between the line and its surroundings.

3 DERIVATION OF FILM CHARACTERISTIC CONSTANTS BY AFD^*_{li}-BASED METHOD

3.1 AFD^*_{li}-based method utilizing drift of line end

In a via-connected line, there are no incoming and no outgoing of atoms at the cathode end and the anode one, respectively, because the atomic flow is intercepted by the vias. As the result, the edge of cathode end of straight line drifts in the direction of electron flow. Schematic illustration of the drift of the cathode end of line is shown in Fig.1, where x=0 indicates initial cathode end position and Δx an infinitesimal length. The value of Δx is given by drifted length, l_d, being equally divided by a large number m. If the atomic flux is a function of coordinate x, which is affected by a temperature distribution along the x-axis, the atomic flux at $x=l_d$, $J|_{x=l_d}$, is approximately expressed by

$$J|_{x=l_d} = J_0 + \sum_{n=1}^{m} \frac{dJ_{n-1}}{dx} \cdot \Delta x \tag{3}$$

where J_n is the atomic flux at $x=n\Delta x$ ($n=1,2,\cdots,m$) and J_0 represents the atomic flux at the line-end. Because the amount of l_d is very small in comparison with the line-length, dJ_{n-1}/dx can be regarded as being constant ($=dJ_0/dx$) within the drifted region. In this case, eqn (3) is simplified as follows:

$$J\Big|_{x=l_d} = J_0 + \frac{dJ_0}{dx} \cdot l_d = J_0 + AFD^*_{li}\Big|_{str} \cdot l_d \tag{4}$$

where $\sum \Delta x$ and dJ_0/dx are replaced by l_d and $AFD^*_{li}|_{str}$, respectively. The symbol $AFD^*_{li}|_{str}$ represents the parameter AFD^*_{li} simplified for straight line end in which the y-components of current density, temperature gradient, atomic density gradient and its gradient are neglected by considering straight shaped line. It can be assumed that the drifted volume has disappeared through a cross section at $x=l_d$ with the atomic flux, $J|_{x=l_d}$. Therefore, by multiplying the line-width, w, line-thickness, $thick$, atomic volume, Ω, and the time to annihilate the volume of drifted region, t_d, to eqn (4), the volume of drifted region, that is $l_d \cdot w \cdot thick$, can be expressed. Consequently, the drift velocity of the line end, v_d ($=l_d/t_d$), is expressed by

$$v_d = (J_0 + AFD^*_{li}\big|_{str} \cdot l_d)\Omega \tag{5}$$

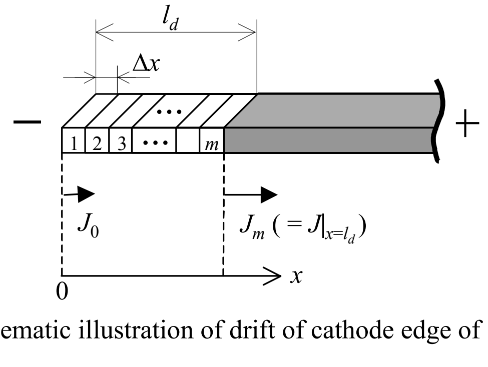


Figure 1: Schematic illustration of drift of cathode edge of straight line.

The film characteristic constants included in the formula of AFD^*_{li} are Q_{li}, Z^*, C^*_{li} and κ. According to Blech [5], the atomic density gradient depends on the length of the line, and is inversely proportion to the length. During the initial stage of electromigration damage, the atomic density distribution is assumed to be linear along the line and constant. The product of κ and $\partial N/\partial x$ is determined as a characteristic depending on the length of the straight line.

The film characteristics $Q^*_{li}[=Q_{li}-\sigma_T\Omega]$, Z^*, C^*_{li} and $\kappa\cdot\partial N/\partial x$ are experimentally determined by utilizing the drift phenomenon of the cathode end as follows. Accelerated tests are performed for a certain period of time. The test lines are subjected to high-density electric current and high substrate temperature under their four conditions at least. The drifted length of the edge is measured after current stressing for a certain period of time. The drift velocity is obtained by dividing the drifted length by a net current-applying time. The net current-applying time is obtained by subtracting the incubation period, during which there was no drift of the end and no void nucleation, from the current supplying time. The unknown film characteristic constants in AFD^*_{li} can be obtained by the least-squares method approximating the measured drift velocity with theoretical one in eqn (5). Namely, the characteristics are determined so that the following sum takes the minimum value:

$$F^*_{li}\big|_{end} = \sum_k \sum_l \Big[v_d\big|_{kl} - \big\{ J_0\big|_k + (AFD^*_{li}\big|_{str})_k \cdot l_d\big|_{kl} \big\}\Omega \Big]^2 \qquad (6)$$

where subscripts k and l are the condition number and the number of data measured in each experimental condition, respectively.

3.2 Application of AFD^*_{li}-based method

The Al line specimens were fabricated to imitate via-connected line as follows. The TiN layer was deposited by sputtering system on the silicon substrate covered with silicon oxide and, continuously, Al film was deposited by vacuum evaporation on TiN. The specimens were patterned by conventional photolithography and etched by reactive ion etching (RIE). The small regions of Al layer at both test line-ends were chemically etched and then TiN layer was bared. After the metal line was constructed, the specimens were annealed at 673K for 90min in order to form the bamboo-like microstructure. Next, tetraethyl orthosilicate (TEOS) film was deposited over the specimen's surface by plasma enhanced chemical vapor deposition (PE-CVD). The dimensions of the metal line specimen made are shown in Fig.2. Two kinds of lines with different line-length were fabricated. The line-length of Sample L and that of Sample S are 38.1 and 18.9 μm, respectively. From the observations of the microstructure by focused ion beam (FIB) equipment, it was confirmed that the metal line used was bamboo-like structured as shown in Fig.3.

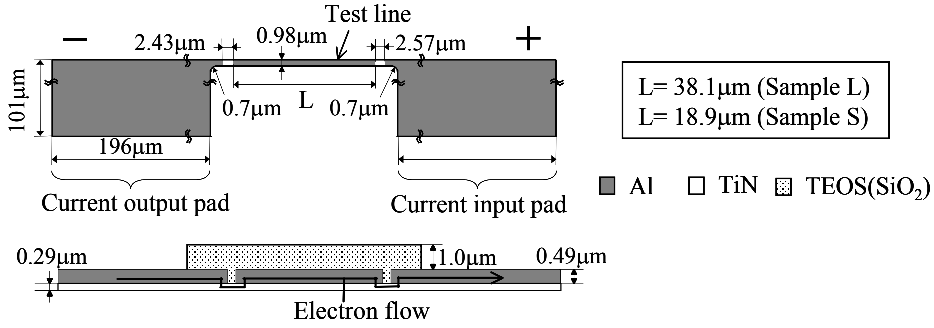


Figure 2: The metal line specimen used in the experiment.

The accelerated tests were performed to measure the drift velocity. To obtain the incubation period, the change in electrical potential drop in the line was monitored. The three different substrate temperatures, 508, 523 and 538 K, were selected. In the case of Sample L, for each temperature, the metal lines were subjected to direct current with density of 3.0 MA/cm^2 (Condition-1, -2 and -3). In addition, the test was performed under a current density of 2.5 MA/cm^2 and the substrate temperature of 523K (Condition-4). In the case of Sample S, the direct current with density of 4.5 MA/cm^2 was supplied under the substrate temperatures of 508, 523 and 538K as Condition-1, -2 and -3, respectively. In addition, the test was performed under a current density of 4.8 MA/cm^2 and the substrate temperature 523K as Condition-4. Ten specimens were used under each testing condition for both samples. Before and after electric current was supplied, the images near the cathode end of lines were taken by a laser microscope as shown in Fig. 4. The distance from current output pad to cathode edge of testing part before current stressing and that distance after current stressing were measured. And then the drift-length was got by subtracting each other. From the drift-length divided by the net current-applying time, the drift velocity was obtained. The experimental data of the drift velocity were input into eqn (6) and the unknown film characteristics in AFD^*_{li} were optimized by using the least-squares method.

3.3 Derived constants and discussion

The obtained constants are listed in Table 1. The values, 0.5-0.95 eV, have been obtained as the activation energy for the same material system as that in this study by Proost et al.[3], Schreiber[7] and Munari et al.[8]. The values of Q^*_{li} obtained in this study were within the range of the values reported. On the other hand, the values of Z^* obtained were within the range of the previously reported values, $-1\sim-15$ (Tu[9] and Wang et al.[10]).

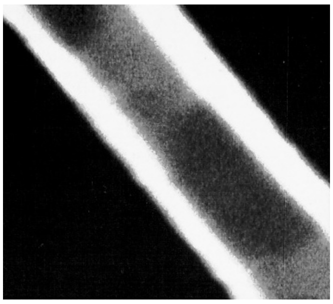
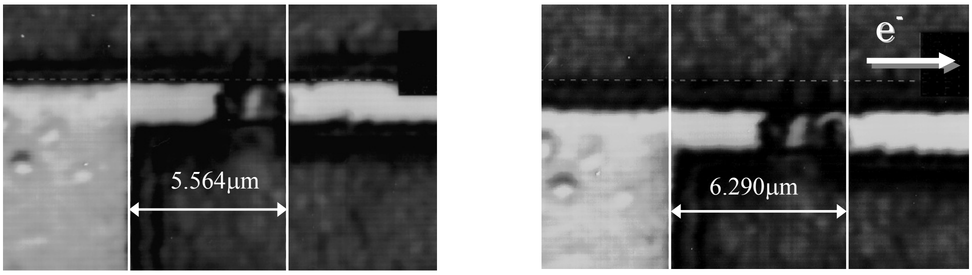


Figure 3: The observation of the bamboo structure.



(a) Before current supply

(b) After current supply

Figure 4: Observation of line end before and after current supplying (Sample S).

Table 1: The film characteristic constants obtained by AFD^*_{li}-based method.

	Q^*_{li}[eV]	Z^*	C^*_{li} [Kμm^2/Js]	$\kappa\cdot\partial N/\partial x$ [J/μm^7]
Sample L	0.76	-1.3	2.0×10^{26}	0.91
Sample S	0.75	-1.2	2.2×10^{26}	1.8

From comparison between Q^*_{li}'s value of Sample L and that of Sample S, it was found that Q^*_{li}'s values of these samples agreed well, and thus Q^*_{li} functions as the characteristic constant which is independent of line-length and dependent on only film character. In comparisons of Z^* and C^*_{li} of Sample L with those of Sample S, these values were almost the same. Therefore, it was found that Z^* and C^*_{li} also functioned as the characteristic constants independent of line-length. On the other hand, the $\kappa\cdot\partial N/\partial x$'s value of Sample S was about two times as large as that of Sample L, and only $\kappa\cdot\partial N/\partial x$'s value seems to be dependent upon the line-length in Table 1. According to Blech [5], atomic density gradient is inverse proportion to the line-length. Therefore, it was found that $\kappa\cdot\partial N/\partial x$ functioned appropriately as the characteristic depending on line-length. In this way, it was concluded that the film characteristic constants were appropriately determined by AFD^*_{li}-based method.

4 CONCLUSIONS

The film characteristic constants included in AFD^*_{li} were obtained for two metal lines with different lengths so that the drift velocity calculated by AFD^*_{li} agreed with measured one. Through the discussion on the validity of the obtained constants, it was shown that AFD^*_{li}-based method was able to determine the film characteristics appropriately.

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