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Atomic flux divergence in bamboo line for predicting initial formation of voids and hillocks

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Abstract

A calculation method of the atomic flux divergence due to electromigration, AFD_{gen}, has been proposed considering two-dimensional distributions of current density and temperature and also simply considering the line structure of not only polycrystalline line but also bamboo line. The validity of AFD_{gen} for bamboo lines has been verified in comparison of void formation calculated by using AFD_{gen} with experimental results, and it has been shown that void formation in bamboo line is able to be predicted by using AFD_{gen}. In this study, angled bamboo lines are treated for prediction of hillock formation, and hillock formation predicted by using AFD_{gen} is compared with that measured in experiment. In addition to the verification of void prediction, the usefulness of the prediction method for electromigration damage using AFD_{gen} is discussed in more detail. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

Electromigration is one of the key reasons of metal line failure with scaling down of packaged silicon integrated circuit. It is essential to predict the electromigration damage in order to secure reliability of the integrated circuit.

We have developed a formulation of the divergence of atomic flux due to electromigration by considering two-dimensional distributions of current density and temperature and also simply considering the line structures of not only polycrystalline line but also bamboo line [1]. The validity of the atomic flux divergence, AFD_{gen}, for bamboo line has been verified in the light of comparison of void formation calculated by using AFD_{gen} with experimental results, and it has been shown that void formation in bamboo line is able to be predicted by AFD_{gen} [2]. The growth of void leads to metal line failure. Prediction method of the bamboo line failure was recently proposed [3].

In this study, angled bamboo lines are treated for prediction of initial hillock formation by using AFD_{gen}. The hillock formation is also problem because hillock growth leads to short circuit. In addition to the verification of void prediction shown in Ref. [2], the usefulness of the prediction method for electromigration damage, that is, void and hillock formations by using AFD_{gen} is discussed in more detail by comparison of hillock formation calculated by AFD_{gen} with that measured in experiment.

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2. AFD_{gen} for bamboo lines

The void and hillock formations in bamboo line are predicted by using AFD_{gen} for bamboo lines [1]. For understanding AFD_{gen}, its derivation is briefly introduced here. The atomic transportation is assumed to be provided by the Huntington–Grone's equation as follows [4]:

$$\boldsymbol{J} = \frac{ND_0}{kT} \exp\left(-\frac{Q_{lat}}{kT}\right) Z^* e\rho\, \boldsymbol{j}, \tag{1}$$

where $\boldsymbol{J}$ is the atomic flux vector, N the atomic density, D_0 a prefactor, k Boltzmann's constant, T the absolute temperature, Q_{lat} the activation energy for lattice, Z^* the effective valence, e electronic charge, ρ the resistivity depending on the temperature and expressed as $\rho = \rho_0\{1 + \alpha(T - T_s)\}$ denoting the resistivity and the temperature coefficient at the substrate temperature T_s by ρ_0 and α, respectively, and $\boldsymbol{j}$ is the current density vector. It is also assumed that the atomic flux divergence in the grain boundary is negligible and the lattice diffusion including surface diffusion by electromigration is dominant in bamboo line, because there are few grain boundaries in bamboo line and those are perpendicular to longitudinal axis of the line. Based on Eq. (1), we can obtain the number of atoms decreasing in unit volume and unit time in the lattice diffusion as

$$\begin{aligned} AFD_{lat} &= \operatorname{div} \boldsymbol{J} \\ &= C_{lat}\,\rho \frac{1}{T^2}\left(\frac{Q_{lat}}{kT} - 1\right) \\ &\quad \times \exp\left(\frac{-Q_{lat}}{kT}\right)\left(\frac{\partial T}{\partial x} j_x + \frac{\partial T}{\partial y} j_y\right), \end{aligned} \tag{2}$$

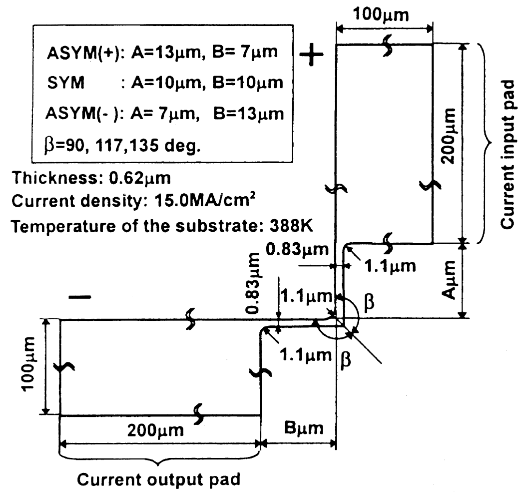
where C_{lat} is expressed by ND_0Z^*e/k and takes negative value, and j_x and j_y are the components of $\boldsymbol{j}$ in Cartesian coordinates x and y. Taking notice of the flux divergence contributing to the void formation, only positive value of AFD_{lat} is extracted. On the other hand, only negative value of AFD_{lat} is extracted taking notice of flux divergence concerning the hillock formation. For example, the atomic flux divergence AFD_{gen} for bamboo lines concerning the hillock formation is derived as

$$AFD_{gen} = \frac{1}{2}(AFD_{lat} - |AFD_{lat}|). \tag{3}$$

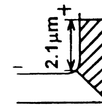
According to Eq. (2), even under high current density and high temperature the flux divergence does not occur if the temperature gradient does not exist. It is noted that the current density and, generally, the temperature gradient exhibit singularity at the corner of the angled line [5].

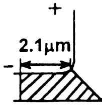
3. Calculation of the flux divergence, AFD_{gen}

The verification of hillock prediction is performed in the same way as that of void prediction [2], and the specimens which have been used in the verification of void prediction are utilized in the present verification of hillock prediction. The seven kinds of Al lines as shown in Fig. 1 are supposed in the prediction. The line width is 0.83 μm and the thickness is 0.62 μm. Denoting the length from the corner to the current input pad by



(a) Seven kinds of angled A1 lines





(b) Objective region for void formation (c) Objective region for hillock formation

Fig. 1. Angled Al lines used for verification of prediction.

A and that from the corner to the current output pad by B, the case that $A = 13$ μm and $B = 7$ μm is called ASYM (+), the case that $A = 10$ μm and $B = 10$ μm is called SYM and the case that $A = 7$ μm and $B = 13$ μm is called ASYM (−), respectively. Furthermore, three kinds of the corner angles, $\beta = 90°$, 117° and 135°, are supposed in each cases. Totally, nine conditions are provided. The metal line specimen for the case of $\beta = 90°$ is common in ASYM (+), SYM and ASYM (−). All specimens are the same in total length of the line. Every metal line has roundness whose radius is 1.1 μm at the inner corner of the testing line part and at the connection between the testing part and the current input/output pads. Also it is assumed that constant DC current, the density of which is 15 MA/cm^2, is applied to the metal line for 1800 s and that the temperature of the substrate and both ends of the line are maintained at 388 K.

Two-dimensional finite element (FEM) analysis of electrothermal problem is performed in order to obtain the current density, the temperature and the temperature gradient which are needed to calculate AFD_{gen}. The heat flow from the line to substrate is considered in the analysis. Let ϕ_e and λ be the electrical potential and the thermal conductivity, where λ is assumed to be constant. The fundamental equations in the problem are given as follows:

Governing equation concerning ϕ_e:

$$\nabla^2 \phi_e = 0. \quad (4)$$

Ohm's law:

$$\boldsymbol{j} = -\frac{1}{\rho_0} \mathrm{grad} \phi_e. \quad (5)$$

Equation of steady-state heat conduction [6]:

$$\lambda \nabla^2 T + \rho_0 \boldsymbol{j} \cdot \boldsymbol{j} + (\rho_0 \alpha \boldsymbol{j} \cdot \boldsymbol{j} - H)(T - T_s) = 0, \quad (6)$$

where H is the constant concerning the heat flow from the line to the substrate and $\nabla^2 = \partial^2/\partial x^2 + \partial^2/\partial y^2$.

The constants concerning film characteristics, which are also necessary for the calculation of AFD_{gen}, are determined experimentally by using the straight shaped metal line, $\beta = 90°$. The constants ρ_0 and α are obtained as 4.45×10^{-2} Ω μm and 0.00305 K^{-1} at $T_s = 388$ K by measuring the electrical resistance of the line. The activation energy, Q_{lat}, is given as the slope of a plot of $\ln VT^2/\rho$ versus $1/T$, where V takes the volume of the void measured within a region at cathode side end of the line in any three cases of the substrate temperatures. The volume of void is measured by atomic force microscopy (AFM) after applying current for a certain time. Thus Q_{lat} is obtained as 0.93 eV. The constant C_{lat} is given by equating the calculated volume of void at one condition with the void volume obtained from the relationship between $\ln VT^2/\rho$ and $1/T$. In this way, the unknown film-characteristic constants are determined from only the simple experiment using the straight line.

The constants H and λ, which are concerned with the simulation of the temperature distribution in the metal line, are determined so that each electrical potential drop calculated based on the temperature simulation in the straight line and angled line agrees with the each measured value. It is known that the thermal conductivity of thin film is lower than that of bulk [7], and the value obtained in this study, $\lambda = 1.85 \times 10^{-4}$ W/(μm K), is also lower than the bulk's value, 2.33×10^{-4} W/(μm K).

The flux divergence, AFD_{gen}, is calculated for each condition. The total volumes of initial voids and also initial hillocks within respective objective regions shown in Fig. 1 are predicted by multiplying the current applying time, the atomic volume and the line thickness to the AFD_{gen} integrated over each objective region. The verification of void prediction is performed taking note of corner's anode side shown in Fig. 1(b) and the hillock prediction is verified taking note of corner's cathode side shown in Fig. 1(c). In the corner's anode side, void can be formed with ease since the temperature gradient to electron flow takes positive value, and hillock can be formed with ease in the corner's cathode side since the temperature gradient is negative to electron flow.

4. Experiment

For verification, the experiment was performed with seven kinds of metal lines under the same

Fig. 2. An example of FE-SEM (ECC mode) micrograph of the specimen.

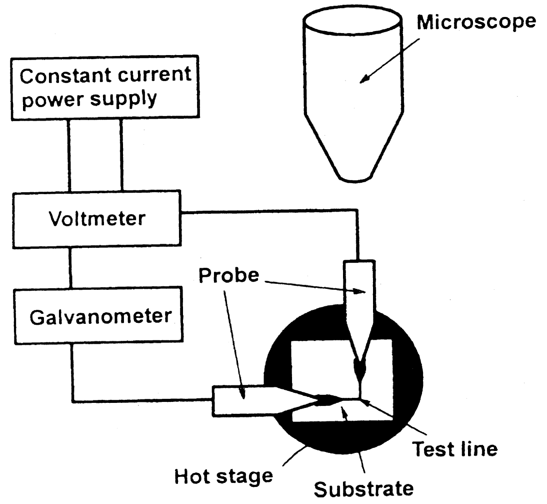
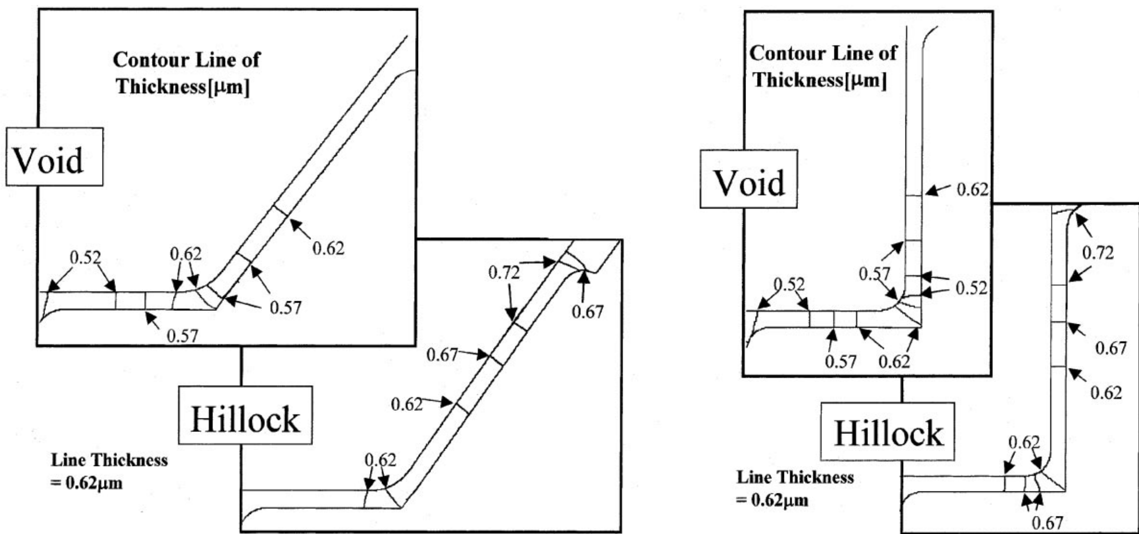
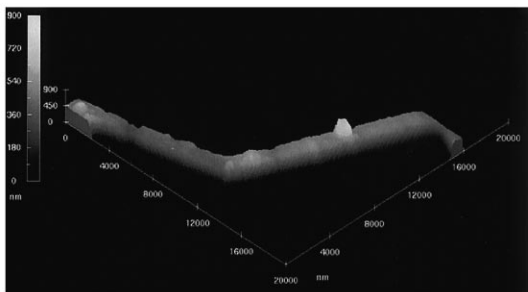
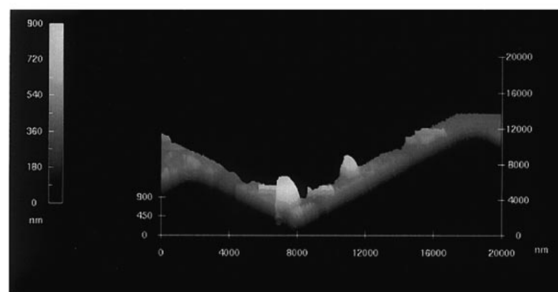


Fig. 3. Experimental set-up.







(a) ASYM(+), β =117deg.

(b) ASYM(+), β =135deg.

Fig. 4. Qualitative comparison of prediction with measured geometry.

condition as the prediction. Al thin film was deposited by vacuum evaporation on the silicon substrate that was covered with silicon oxide. After patterning by photolithography the metal line was annealed at 673 K for 1 h. The specimens were confirmed to be bamboo structured by electron channeling contrast (ECC) mode observation in field emission-scanning electron microscope (FE-SEM) as shown in Fig. 2. The experiment was performed by using a set-up shown in Fig. 3. Nine or eight specimens were used per condition. The volume of metal line was measured by AFM before and after applying current for 1800 s. The volumes of the void and hillock formed in the respective objective regions were obtained by substracting the line volume before current applying from the line volume after current applying.

Examples of AFM image of the metal line geometry after current applying and the calculated line geometry are shown in Fig. 4. From a viewpoint of qualitative comparison of prediction with measured geometry, it seems that voids and hillocks are formed at the expected region. For the quantitative comparison the relationship between the void volume measured near the corner and the predicted one is shown in Fig. 5, and it has already been reported in Ref. [2]. The relationship between the hillock volume measured near the corner and the predicted one is shown in Fig. 6. The predictions of both void and hillock formations in all

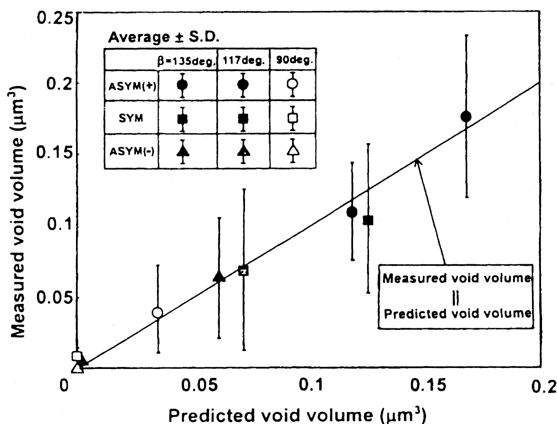


Fig. 5. Relationship between the measured void volume and the predicted one.

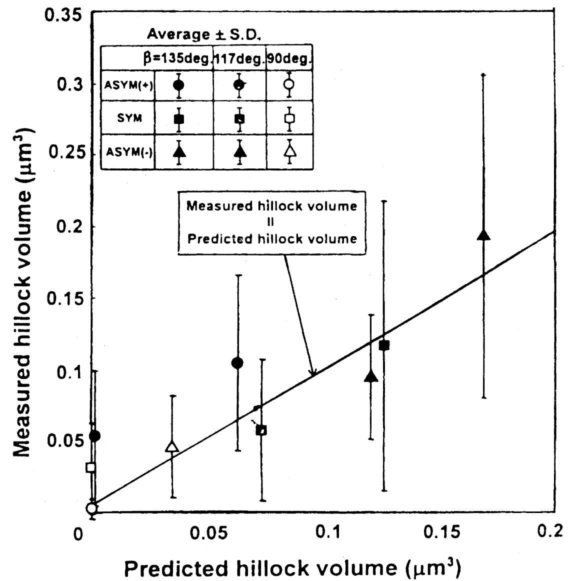
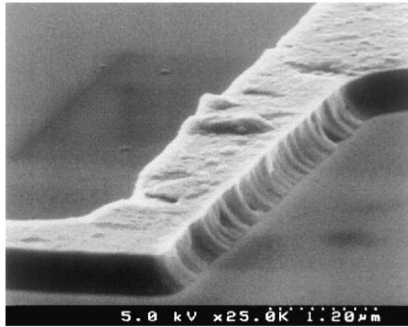


Fig. 6. Relationship between the measured hillock volume and the predicted one.

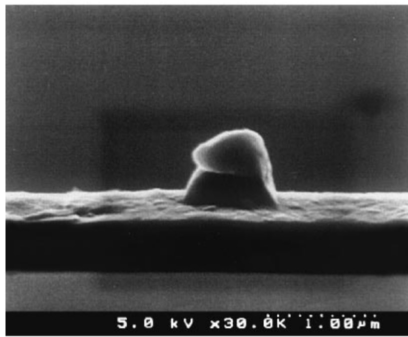
conditions correlate well with the experimental values. Further all experimental data are arranged linearly by the predictions in spite of the difference in the line shape, which makes differences in distributions of temperature and current density. The measured hillock volume is somewhat greater than predicted one in some cases and the scatter band of the measured hillock volume is wider than that of void volume. According to our observation, some hillocks are formed so as to swell the metal line and others are lump-like shaped as shown in Fig. 7. The scanning of lump-like hillock is difficult for AFM. That is why the volume of hillock is evaluated greater by AFM. From these, the rationality of AFD_{gen} for bamboo lines was experimentally verified in more detail, and the usefulness of the prediction method for electromigration damage, that is, void and hillock formations in bamboo line by using AFD_{gen} was shown.

5. Conclusions

In addition to the verification of void prediction which has already been reported, the verification



(a) Swelling like hillock



(b) Lump like hillock

Fig. 7. FE-SEM observation of hillocks.

of hillock prediction was performed. The volume of hillock formed near the corner was measured by AFM in the experiment and also was calculated by using AFD_{gen} in the prediction. The predictions of both void and hillock formations in all conditions correlated well with the experimental values. From these, the validity of the AFD_{gen} for bamboo lines was verified in more detail, and the usefulness of the prediction method for electromigration damage, that is, void and hillock formations in bamboo line by using AFD_{gen} was shown.

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