THEORETICAL ANALYSIS OF VACANCY TRANSPORT COMBINED WITH ELECTROMIGRATION AND STRESS INDUCED VOIDING

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PURPOSE

Electromigration (EM) and stress-induced voiding have become significant in recent LSI interconnections due to the increase in current density and residual stress [1-3]. Many works have been carried out to clarify the relationship between EM and residual stress [4-6]. The present authors have reported the numerical analysis of vacancy transport based upon the mass balance equation [7]. This paper concludes that the behavior of vacancy transport by EM is influenced by residual stress. In this paper, an equation for vacancy transport is proposed to include the effect of residual stress. A computer-aided simulation and an in-situ observation test are conducted to discuss the quantitative relationship between current density and residual stress. [*Keywords:* electromigration, residual stress, numerical analysis, in-situ observation]

NUMERICAL ANALYSIS

The driving force for vacancy transport by an electric field is expressed in eq.1 [8], and the residual stress in eq.2 [5]. The equation for vacancy transport can be expressed to consider the effect of electric field and residual stress in eq.3.

$$F_{EM,vac} = -eZ^{*}E, \quad (1)$$

$$F_{s,vac} = \nabla\sigma_p \Delta V^{*}, \quad (2)$$

$$\frac{\partial C_{vac}}{\partial t} = -D_v \nabla\cdot\left(-\nabla C_{vac} - \frac{eZ^{*}}{kT}C_{vac}\cdot E + \frac{\Delta V}{kT}C_{vac}\nabla\sigma_p\right), \qquad (3)$$

where $F_{s,vac}$ is the driving force for vacancy transport by residual stress, $F_{EM,vac}$ is the driving force for vacancy transport by electric field, σ_p is the hydrostatic stress, ΔV^{*} is the volume change on insertion of a vacancy, eZ* is an effective atomic number, E is the electric field, D_v is the diffusion coefficient of the vacancies, C_{vac} is the concentration of vacancies, and k is the Boltzman constant.

The 1st term of eq.3 indicates a divergence of vacancy concentration, the 2nd term indicates a divergence of electric field and the 3rd term indicates a divergence of residual stress. An electro-hydrodynamic analysis is applied to obtain the divergence of the electric field and the finite elemental method (FEM) is used to obtain the distribution of hydrostatic stress. The numerical analysis using the finite differential method (FDM) has been established by the present authors [8] and a similar technique has been applied to demonstrate the distribution of vacancy concentration with various combinations of current density and residual stress. The analysis assumes a pre-existing round-shaped-defect to give a concentration of residual stress. Fig.1 shows the distribution of hydrostatic stress around the defect when a uniaxial stress is applied. This result reveals that the maximum hydrostatic stress is observed at a tip of the defect.

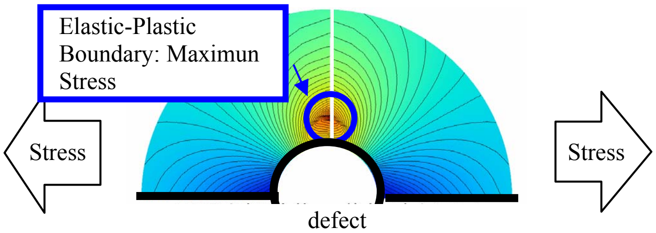

FIGURE 1.HYDROSTATIC STRESS DISTRIBTUION AROUND THE PRE-EXISING NOTCH

When a current density is applied without a residual stress, vacancies concentrate at the cathode end (see Fig.2(A)).

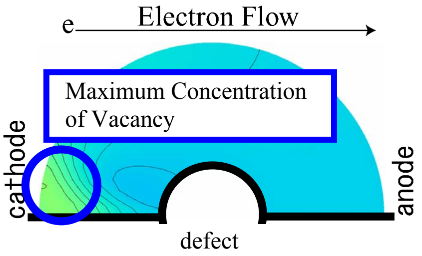

FIGURE 2(A). VACANCY DISTRIBUTION OF RESIDUAL STRESS=0 MPA AND CURRENT DENSITY=7.0× 10^6A/CM^2

When both residual stress and current are applied, vacancies concentrate at the cathode side of the area where the maximum residual stress occurs (see Fig.2(B)). Increasing the residual stress makes the site of the maximum vacancy concentration approach the area of maximum hydrostatic stress. When no current density is applied, vacancies concentrate at the area of the maximum hydrostatic stress and this result is consistent with the stress-induced voiding model [9].

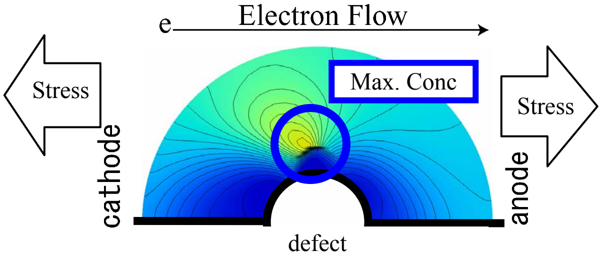

FIGURE 2(B). VACANCY DISTRIBUTION OF RESIDUAL STRESS=400MPA AND CURRENT DENSITY=2.0× 10^6A/CM^2

These results revealed that behavior of vacancy transport is determined by a combination of residual stress and current density. This numerical analysis of the equation for vacancy transport with residual stress and electric field is able to simulate the behavior of vacancy transport under various conditions of residual stress and current density.

Application to Black's equation

The critical time for void formation is defined as the time when the concentration of vacancies reaches a certain value which is assumed to generate the voids. Fig.3 shows the relationship between the critical time for void formation, t_{cr} and current density. As shown in Fig.3, the time to generate voids is proportional to the current density. The current density exponent n=1 is reported when voiding growth dominates the EM lifetime [6, 10]. The following in-situ observation test result on a line with a defect showed void nucleation appeared in less than 10% of the EM lifetime, so that the current exponent n=1 obtained by the numerical analysis is consistent with Black's equation.

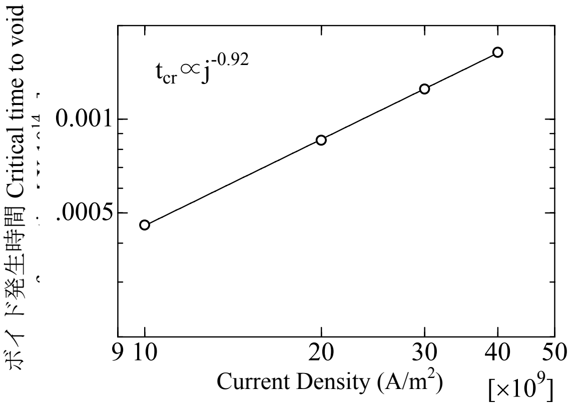

FIGURE 3.RELATIONSHIP BETWEEN THE CRITICAL TIME OF VOID FORMATION AND CURRENT DENSITY

IN-SITU OBSERVATION EXPERIMENTAL RESULT

To confirm the validity of the proposed equation and analysis, an in-situ observation experiment has been carried out to determine the mechanism of void generation and growth during EM. An AlSiCu line with an initial triangular notch defect is prepared to enable the detection of void formation and investigate the effect of residual stress concentration. Moreover, it was thought that the wide line might behave as a heat sink for joule heating. The EM acceleration test was carried out with conditions of current density=2MA/cm^2 and stage temp.=200℃. A void began to be generated after less than 10% of the EM lifetime. Fig.4 shows void formation during the EM test. Many voids are observed around the cathode side of the notch defect and failure occurs around here. This result is in good agreement with the result in Fig.2 (B). On the other hand, EM failure occurs at the cathode end in a straight interconnection without a defect [11]. Considering these results, we conclude that the numerical analysis of this paper is useful to predict the behavior of EM voiding under various combination of residual stress and current density.

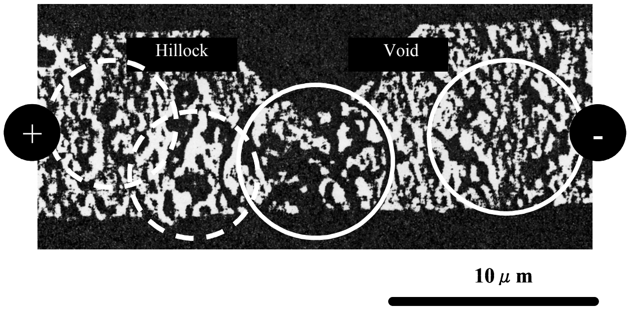

FIGURE 4. PHOTOGRAPH OF EM VOIDING AND EM FAILURE

CONCLUSIONS

A vacancy transport equation has been proposed, considering the effect of residual stress and electric field. A numerical analysis has been carried out to determine the vacancy distribution with various combinations of residual stress and current density. When the residual stress is dominant, voids are generated at the cathode side of the area where the maximum residual stress occurs. When the electric stress dominates, voids are generated at the cathode end. An in-situ observation test has been carried out to determine the void generation and growth during EM tests. Voids are generated and grow around the notch defect where the maximum stress occurs and this result is in good agreement with the result predicted by numerical analysis. The analysis is applied to investigate the current density exponent and the result revealed that the numerical analysis was consistent with Black's equation.

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