JOURNAL OF MATERIALS SCIENCE **35** (2000) 5575 – 5579

Thermomigration as a driving force for instability of electromigration induced mass transport in interconnect lines

C. Q. RU
Department of Mechanical Engineering, University of Alberta, Edmonton, Alberta, Canada T6G 2G8
E-mail: c.ru@ualberta.ca.

Linear instability of electromigration induced mass transport is studied as an intrinsic mechanism of void nucleation and growth in interconnect lines. Heat conduction along the conductor line and between the conductor line and surrounding materials is added to a recent model, proposed by Korhonen.*et al.* (1993) for electromigration induced stress evolution, to examine the role of thermomigration in linear instability of uniform mass transport. The analysis shows that thermomigration is the leading driving force for instability of electromigration-induced mass transport in interconnect lines. This theoretical prediction seems to qualitatively agree with a recent experimental study. These results suggest that thermomigration, which has been ignored in most previous studies, could play a significant role in electromigration failure of interconnect lines.

1. Introduction

Electromigration (EM) has been identified as one of the major causes of failure of interconnect lines in large scale integrated circuits [1–3]. Owing to continuous scaling down in dimensions of typical integrated circuits, electric current density in interconnect lines is increasingly high. As a result, current-induced directional mass transport causes nucleation and growth of voids, especially at flux divergences such as grain boundaries, interfaces and voids, eventually resulting in opens and shorts in integrated circuits. This phenomenon has largely limited further device miniaturization.

EM induced voiding can be understood as a growth process of spatial non-uniformity of mass distribution in conductor lines. Since a stable uniform mass transport tends to suppress growth of spatial non-uniformity whereas an unstable one tends to promote it, nucleation and growth of voids are expected to have intrinsic connection with instability of spatially uniform mass transport. Although it has long been known that preexisting flux divergences can drastically accelerate EM failure, it is unclear whether EM failure could occur even in the absence of any preexisting flux divergence. In fact, there are many physical phenomena in which growth of spatial non-uniformity occurs as a result of instability of spatially uniform state in an "ideal" material without any preexisting defect. For instance, diffusional spheroidization of continuous rods [4] and void formation of epitaxially strained thin-films [5] provide such examples. Therefore, it is of great interest to study intrinsic instability of EM-induced mass transport in interconnect lines without any preexisting defect or void. In connection with this, it should be mentioned that although EM induced mass transport in void-free homogeneous conductor lines has been studied previously [6–8], the related stability issue has not been examined at all. Motivated by these considerations, the present author have recently studied linear instability of uniform mass transport in a defect-free homogeneous conductor line [9]. It is found in [9] that thermomigration (TM) is the leading driving force for linear instability, and the linear instability of uniform mass transport emerges in a defect-free homogeneous conductor when electric current density and temperature are sufficiently high. The study [9] revealed the "intrinsic" aspects of EM-induced failure and the significant role of TM, both of which have not been clearly recognized and addressed in the literature. More recently, it has been noted that theoretical results of [9] seem to be supported qualitatively by a recent experimental work on electric-current induced failure at crack tip in thin-film conductors by Bastawros & Kim [10], where these authors found that "the crack-growth-mode failure of both the Al and Au films are believed to be primarily controlled by Soret diffusion" (thermomigration).

A major shortcoming of the previous model [9] is that it has been based on a simplified continuity equation used in [6–8] which excludes the effect of vacancy sinks and sources in conductor lines. Recently, a new model has been developed by Korhonen *et al.* [11] which takes account of vacancy sinks and sources and then leads to an essentially different continuity equation. Korhonen *et al* 's model has gained considerable attention and been widely regarded as a physically more reasonable model for EM-induced failure (see e.g. [12, 13]). Hence, in the present paper, Korhonen *et al* 's model is used to reexamine linear instability of EM-induced uniform mass transport in a defect-free homogeneous conductor line.

2. Basic equations

Consider a confined homogeneous conductor line lying along the x-axis. Let the vacancy concentration be $N(x, t)$, then the vacancy flux J is given by [1, 2, 6, 14]

$$J = -D\frac{\partial N}{\partial x} + \frac{ND}{kT}F \tag{1}$$

where k is the Boltzmann constant, T is the absolute temperature, F is the driving force, and D is the diffusion coefficient of vacancies as follows

$$D = D^* \exp[-E_\mathrm{a}/(kT)] \tag{2}$$

here E_a is the activation energy, and D^* is a material constant. The driving force is [1, 2, 14]

$$F = -\frac{\partial \mu}{\partial x}, \quad \mu = \mu_0 + Z^* q\varphi - \Omega\sigma + Q^* \ln T \tag{3}$$

where μ is the chemical potential, μ_0 is the reference value, q is the element charge, Z^* is the effective charge coefficient, φ is the electrical potential, Ω is the atom volume, σ is the mean stress, and Q^* is the heat of transport. Here, because there is no surface or bulk flux divergence, surface and interface diffusions are excluded.

Following Korhonen *et al*. [11] (see also Clement & Thompson [12] and Lloyd [13]), the vacancies are assumed to be in equilibrium with the stress, then

$$N = N^* \exp\left[\frac{\Omega\sigma}{kT}\right] \tag{4}$$

where N^* is the equilibrium value when the stress vanishes. The vast majority of transported vacancies annihilate at sinks. As a result, the number of lattice sites is reduced and the atom concentration per unit length decreases. Thus, the continuity equation is of the form [11–13]

$$\frac{\partial N}{\partial t} - \frac{\partial C}{\partial t} = -\frac{\partial J}{\partial x} \tag{5}$$

where C denotes the atom concentration. The second term on the left represents the vacancy sink/source, which has been ignored in some previous models [6–8].

It follows from (1), (3) and (5) that

$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial x}\left[D\frac{\partial N}{\partial x}\right] + \frac{\partial}{\partial x}\left[\frac{ND}{kT}\left(Z^* q\rho j + \Omega\frac{\partial \sigma}{\partial x} - \frac{Q^*}{T}\frac{\partial T}{\partial x}\right)\right] + \frac{\partial C}{\partial t} \tag{6}$$

where ρ is the resistivity, and j the electric current. For a uniform mass transport, the unperturbed electric current, stress, temperature, atom concentration and vacancy concentration are constant along the conductor line. Using the subscript "0" to denote these constants in the unperturbed state, the perturbed state is expressed by

$$\begin{aligned} N &= N_0 + \Delta N(x, t), \qquad C = C_0 + \Delta C(x, t) \\ j &= j_0 + \Delta j(x, t), \qquad \sigma = \sigma_0 + \Delta\sigma(x, t), \\ T &= T_0 + \Delta T(x, t) \end{aligned} \tag{7}$$

where Δ denotes the variations. Thus, the linear perturbed equation of (6) is

$$\begin{aligned} \frac{1}{D_0}\frac{\partial \Delta N}{\partial t} - \frac{1}{D_0}\frac{\partial \Delta C}{\partial t} &= \frac{\partial^2 \Delta N}{\partial x^2} + \frac{\Omega N_0}{kT_0}\frac{\partial^2 \Delta\sigma}{\partial x^2} \\ &- \frac{Q^* N_0}{kT_0^2}\frac{\partial^2 \Delta T}{\partial x^2} + \left(1 - \frac{E_a}{kT_0}\right)\frac{J_0}{D_0 T_0}\frac{\partial \Delta T}{\partial x} \\ &+ \frac{Z^* q\rho}{kT_0}\left[j_0\frac{\partial \Delta N}{\partial x} + N_0\frac{\partial \Delta j}{\partial x}\right] \end{aligned} \tag{8}$$

where the terms on the right represent the effects of self-diffusion, stress diffusion, TM and EM, respectively, and J_0 is the uniform vacancy flux of the unperturbed state given by

$$J_0 = -D_0\frac{N_0}{kT_0}Z^* q\rho j_0 > 0 \tag{9}$$

On the other hand, it follows from (4) that

$$\frac{\Delta N}{N_0} = \frac{\Omega}{kT_0}\Delta\sigma \tag{10}$$

where, because the vacancy concentration depends largely on the stress, the influence of temperature variation has been omitted [12]. In addition to (8) and (10), other three equations are needed for five variations defined in (7). They can be derived as follows.

2.1. Stress

For a confined conductor line, because any volume change is not permitted, the change of the atom concentration is transformed into a change of the stress. Hence, the variation of stress is proportional to the volume strain caused by the variation of atom concentration. Thus [11–13]

$$\Delta\sigma = -B\frac{\Delta C}{C_0} \tag{11}$$

where B is an elastic modulus depending on the geometry of the conductor line. On using (10) and (11), ΔC and $\Delta\sigma$ can be expressed by ΔN as follows

$$\Delta C = -\frac{kC_0 T_0}{B\Omega N_0}\Delta N, \quad \Delta\sigma = \frac{kT_0}{\Omega N_0}\Delta N \tag{12}$$

2.2. Electric current

The product of atom concentration and current density must be constant throughout the conductor line. Thus, we have

$$\frac{\Delta j}{j_0} = \frac{-\Delta C}{C_0} = \frac{kT_0}{B\Omega N_0}\Delta N \tag{13}$$

where C_0 is the atom concentration in the unperturbed state.

2.3. Heat Conduction

Finally, temperature distribution along the conductor line is described by the modified heat conduction equation given by [15, 16]

$$c\frac{\partial \Delta T}{\partial t} = K\ \frac{\partial^2 \Delta T}{\partial x^2} + 2j_0\rho\Delta j - h\Delta T, \quad h > 0 \tag{14}$$

where c is the specific heat, K is the heat conductivity of the conductor line, and h is a constant describing heat dissipation through the surrounding materials at the constant temperature T^*. The linear equations (8), (12, 13, 14) provide the basic relations for linear instability analysis.

3. Instability analysis

To identify the driving forces for linear instability, several diffusion mechanisms of major interest are examined respectively.

3.1. Stress gradient-driven diffusion

Blech [17] found that stress gradient provides a back diffusion to EM-driven void growth. On using (12), the stress-gradient term on the right of (8) becomes

$$\frac{\Omega N_0}{kT_0}\ \frac{\partial^2 \Delta\sigma}{\partial x^2} = \frac{\partial^2 \Delta N}{\partial x^2} \tag{15}$$

Hence, the effect of stress diffusion is simply to double self-diffusion. In particular, if only the stress diffusion is considered, (8) and (12) give

$$\left[1 + \frac{kT_0C_0}{N_0\Omega B}\right]\frac{1}{D_0}\ \frac{\partial \Delta N}{\partial t} = 2\ \frac{\partial^2 \Delta N}{\partial x^2} \tag{16}$$

Let $\Delta N(x,t) = e^{\lambda t}e^{imx}$, where λ is a complex number whose real part determines the rate of growth of the perturbation, and m is a real wave-number. It follows from (16) that

$$\lambda = \frac{-2D_0m^2}{\left[1 + \frac{kT_0C_0}{\Omega BN_0}\right]} < 0 \tag{17}$$

Hence, any perturbation will decay with time and then the uniform mass transport is stable.

3.2. Thermomigration (TM)

Almost all previous works have ignored the role of TM in EM failure. This is perhaps due to the fact that the magnitude of TM flux is usually much smaller than EM. However, it is seen from (6) and (8) that the driving force for linear instability is determined by the gradient of the flux, rather than the flux itself. In fact, as stated in a recent experimental work by Bastawros & Kim (1998), there is strong evidence that TM could play a significant role in EM-induced failure in conductor lines. Here, to study the role of TM, we first omit EM. Thus, the Equation (8) becomes

$$\left[1 + \frac{kT_0C_0}{N_0\Omega B}\right]\frac{1}{D_0}\ \frac{\partial \Delta N}{\partial t} = 2\frac{\partial^2 \Delta N}{\partial x^2} - \frac{Q^*N_0}{kT_0^2}\ \frac{\partial^2 \Delta T}{\partial x^2} \tag{18}$$

The model (5) [11–13] assumes that the effect of transported vacancies is to reduce the atom concentration, but not to increase the vacancy concentration. Therefore, the ratio (N_0/C_0) is usually so small compared to unity that [11, 12]

$$\frac{kT_0C_0}{N_0\Omega B} \gg 1 \tag{19}$$

Thus, combining (13), (14) and (18) leads to a single equation for ΔT. Let $\Delta T(x,t) = e^{\lambda t}e^{imx}$, one can obtain a second-order eigenequation for λ as

$$c\lambda^2 + \left[h + Km^2 + \frac{2cD_0N_0B\Omega}{kC_0T_0}m^2\right]\lambda + \frac{2m^2N_0D_0}{kC_0T_0}\left[B\Omega(h + Km^2) - \frac{\rho j_0^2 Q^*}{T_0}\right] = 0 \tag{20}$$

It turns out that the root λ is given by

$$\lambda = \frac{-\left[h + Km^2 + \frac{2cD_0N_0B\Omega}{kC_0T_0}m^2\right] \pm\sqrt{\left[h + Km^2 + \frac{2cD_0N_0B\Omega}{kC_0T_0}m^2\right]^2 - \frac{8cm^2N_0D_0}{kC_0T_0}\left[B\Omega(h + Km^2) - \frac{j_0^2\rho Q^*}{T_0}\right]}}{2c}$$

which has positive real part when and only when

$$\frac{j_0^2\rho Q^*}{B\Omega hT_0} > 1 \tag{21}$$

The condition (21) indicates that the heat conduction between the conductor line and the surrounding media (characterized by the constant h) is essential for TM-driven stability. Here, it should be reminded that the heat conduction along the conductor line is also taken into account in the present model. However, the heat conductivity K of the conductor does not enter the condition (21) because the most unstable perturbations are charactered by vanishingly small wavenumbers for which the role of the heat conductivity along the conductor line becomes less important. Indeed, it is expected that the heat conduction along the conductor line could play a significant role when perturbations of finite wavelength are considered.

Note that the balance between Joule heating and heat conduction between the conductor line and the surrounding materials in the unperturbed state gives

$$h = \frac{\rho j_0^2}{T_0 - T^*} \tag{22}$$

Substitution of (22) into (21) yields the condition for TM driven instability as follows

$$Q^* > B\Omega \frac{T_0}{T_0 - T^*} \tag{23}$$

Hence, TM-driven instability occurs only if the value of the heat of transport is sufficiently high. For instance, if we take Q^*=1 ev (see Ho [18] and Christou [19]), both sides of (23) have the same order of magnitude, even though the value of $B\Omega$ is larger than 1 ev and then the instability condition (23) is likely to fail when Q^*=1 ev.

3.3. Electromigration (EM)

Now, to isolate the role of EM, TM is excluded. Thus, the Equation (8) becomes

$$\begin{aligned} \frac{1}{D_0}\frac{kC_0T_0}{N_0B\Omega}\frac{\partial \Delta N}{\partial t} &= 2\frac{\partial^2 \Delta N}{\partial x^2} \\ &+ \left(1 - \frac{E_a}{kT_0}\right)\frac{J_0}{D_0T_0}\frac{\partial \Delta T}{\partial x} \\ &+ \frac{Z^* q\rho}{kT_0}\left[j_0\frac{\partial \Delta N}{\partial x} + N_0\frac{\partial \Delta j}{\partial x}\right] \end{aligned} \tag{24}$$

In a similar way, the index λ can be obtained as

$$\lambda = \frac{-(A_1 + A_2 + iB_1) \pm \sqrt{(A_1 + A_2 + iB_1)^2 - 4A_1A_2 - i2B_2}}{2c} \tag{25}$$

where A_1, A_2, B_1 and B_2 are some non-negative numbers defined by

$$A_1 = h + Km^2, \qquad A_2 = \frac{2cD_0N_0B\Omega}{kC_0T_0}m^2,$$
$$B_1 = \frac{mcJ_0}{C_0}\left(\frac{B\Omega}{kT_0} + 1\right) \tag{26}$$
$$B_2 = 2cmJ_0\left[\frac{2\rho j_0^2}{T_0C_0}\left(\frac{E_a}{kT_0} - 1\right) + \frac{(h + Km^2)}{C_0}\left(1 + \frac{B\Omega}{kT_0}\right)\right]$$

Note that

$$\begin{aligned} &(A_1 + A_2 + iB_1)^2 - 4A_1A_2 - i2B_2 \\ &= \left[A_1 + A_2 + i\left[B_1 - \frac{B_2}{(A_1 + A_2)}\right]\right]^2 \\ &+ \left[B_1 - \frac{B_2}{(A_1 + A_2)}\right]^2 - 4A_1A_2 - B_1^2 \end{aligned}$$

In addition, it can be proved (see [9]) that for arbitrary complex number z and any strictly positive number δ, the inequality holds

$$|\mathrm{Re}[\sqrt{z}]| \le |\mathrm{Re}[\sqrt{z + \delta}]|$$

where the equality holds only when the right-hand side is zero. In particular, the validity of the above inequality for any complex number z implies that

$$|\mathrm{Re}[\sqrt{z}]| \ge |\mathrm{Re}[\sqrt{z - \delta}]|$$

Using these results, it can be verified that the index λ with positive real part exists if and only if

$$\left[B_1 - \frac{B_2}{(A_1 + A_2)}\right]^2 > 4A_1A_2 + B_1^2 \tag{27}$$

Further, it can be verified that the most unstable perturbation is associated with vanishingly small m. In this case, the instability condition (27) becomes

$$\begin{aligned} &cJ_0^2\left[\frac{2}{T_0C_0}\frac{E_a}{kT_0} + \frac{1}{C_0(T_0 - T^*)}\frac{B\Omega}{kT_0}\right]\frac{E_a}{kT_0} \\ &> \frac{\rho j_0^2}{(T_0 - T^*)^3}\frac{D_0N_0B\Omega}{k} \end{aligned}$$

where we have used the relation (22) and the fact that $E_a/(\kappa T_0) \gg 1$, $(B\Omega)/(\kappa T_0) \gg 1$. Further, because E_a is negligible compared to $B\Omega$, the above condition becomes

$$\frac{cD_0}{k^2T_0}(Z^*q)^2\rho\frac{N_0}{C_0}\frac{E_a}{kT_0} > \frac{T_0^2}{(T_0 - T^*)^2} \tag{28}$$

For instance, if $E_a = 0.5$ eV, $Z^* = -15$, $T_0 = 600$ K, $\rho = 3\mu\Omega$ cm, $D^* = 10^{-4}$cm^2/s, and $c = 3$ J/cm^3-K, the right side of (28) is several order of magnitude larger than its left side because that the ratio (N_0/C_0) is at least several order of magnitude smaller than unity. Hence, EM-driven linear instability will not occur under typical physical conditions.

Here, a comparison of (23) with (28) indicates that TM provides the leading driving force for linear instability of uniform mass transport. This suggests that TM could play a significant role in EM-induced voiding. As stated in [9], this result does not conflict with the known fact that the effect of TM on void motion is negligible [18]. In fact, because Joule heating due to current crowding [1, 15, 16, 20] causes an antisymmetric temperature gradient at the void, TM promotes vacancy motion towards the void and then can significantly change the shape and size of the void, even though its effect on the motion of void as a whole is negligible. As mentioned before, a recent independent experiment study [10] on EM induced damage evolution in thin-film conductors appears to provide a convincing support for the significant role of TM predicted by the present model. Here, it should be stated that the role of TM has not been addressed in the literature. In particular, TM has been ignored in almost all recent works on transgranular failure of narrow conductor lines [21–24]. On the other hand, in the spirit of the present model, slit-like voids would cause extremely high local temperature gradient as compared to what circular voids could cause. It seems that this could help us to understand the observed vital slit-like void growth in the direction perpendicular to the conductor line.

4. Conclusions

Based on a modified form of Korhonen *et al*'s model [11], linear instability of EM induced uniform mass transport in a defect-free homogeneous conductor line is studied. Among others, it is found that:

1) Consistent with their known role in void growth in conductor lines, TM and EM are identified to be the major intrinsic driving forces for instability of mass transport. This indicates that the study of instability of mass transport in a defect-free homogeneous conductor line has the potential to identify intrinsic driving forces for EM induced failure.

2) In qualitative agreement with a recent experiment [10] on EM induced failure in conductor lines, the present study reveals that TM plays the dominant role in linear instability of uniform mass transport. This result suggests that TM should be taken into account in the study of EM induced void growth. In particular, this provides a new insight into the study of transgranular slit failure of bamboo-like conductor lines [21–24].

Finally, it should be stated that the present analysis is limited to linearized infinitesimal instability. Strictly speaking, it cannot be applied to finite perturbations, such as a circular or slit-like void. Therefore, an interesting topic for further work is nonlinear instability of mass transport. It is expected that nonlinear analysis could provide useful information about, say, the time-dependent evolution of unstable perturbations, as well as the sensitivity of instability to local imperfections, such as a local debonding between the conductor line and the surrounding materials which would significantly affect local stresses and heat concentration.

Acknowledgment

The financial support of the Natural Sciences and Engineering Research Council of Canada is gratefully acknowledged.

References

1. P. S. HO and T. KWOK, *Report. Progr. Phy.* **52** (1989) 301.
2. D. G. PIERCE and P.G. BRUSIUS, *Microelectron. Reliab.* **37** (1997) 1053.
3. H. OKABAYASHI, S. SHINGUBARA and P. HO, "Stress-induced phenomena in metalization," Fourth international workshop. AIP Conference Proceedings No. 418 (1998).
4. F. A. NICHOLS and W. W. MULLINS, *Trans. AIME* **233** (1965) 1840.
5. B. J. SPENCER, S. H. DAVIS and P.W. VOORHEES, *Phys. Review* B **47** (1993) 9760.
6. M. SHATZKES and J. R. LLOYD, *J. Appl. Phy.* **59** (1986) 3890.
7. J. R. LLOYD and J. KITCHIN, *J. Mater. Res.* **9** (1994) 563.
8. V. M. DWYER, F. S. WANG and P. DONALDSON, *J. Appl. Phy.* **76** (1994) 7305.
9. C. Q. RU, *Acta. Mater.* **47** (1999) 3571.
10. A. F. BASTAWROS and K. S. KIM, *Journal of Electronic Packaging* (ASME) **120** (1998) 354.
11. M. A. KORHONEN, P. BORGESEN, K.N. TU and C.Y. LI, *J. Appl. Phys.* **73** (1993) 3790.
12. J. J. CLEMENT and C. V. THOMPSON, *ibid* **78** (1995) 900.
13. J. R. LLOYD, *Semicond. Sci. Tech.* **12** (1997) 1177.
14. R. KIRCHHEIM, *Acta. Metal.* **40** (1992) 309.
15. Y. S. CHAUG and H. L. HUANG, *J. Appl. Phys.* **47** (1976) 1775.
16. H. A. SCHAFFT, *IEEE Transactions on Electron Devices* **ED-34** (1987) 664.
17. I. A. BLECH, *J. Appl. Phys.* **47** (1975) 1203.
18. P. S. HO, *ibid.* **41** (1970) 64.
19. A. CHRISTOU, in "Electromigration and Electronic Device Degradation," edited by A. Christou, (John Wiley & Sons, Inc. New York 1994) p. 291.
20. S. A. LYTLE and A. S. OATES, *J. Appl. Phys.* **71** (1992) 174.
21. M. SCHIMSCHAK and J. KRUG, *Physical Review Letters.* **80** (1998) 1674.
22. M. R. GUNGOR and D. MAROUDAS, *J. Appl. Phys.* **85** (1999) 2233.
23. D. R. FRIDLINE and A. F. BOWER, *ibid.* **85** (1999) 3168.
24. M. MAHADEVAN and R. M. BRADLEY, *Physical Review* **B 59** (1999) 11037.

Received 8 November 1999
and accepted 5 April 2000