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**A STUDY ON ELECTROMIGRATION BY DRIVING
FORCE APPROACH FOR SUBMICRON COPPER
INTERCONNECT**

ARIJIT ROY

SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING

2007

A STUDY ON ELECTROMIGRATION BY DRIVING FORCE
APPROACH FOR SUBMICRON COPPER INTERCONNECT

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A Study on Electromigration by Driving Force Approach for Submicron Copper Interconnect

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SUMMARY

Electromigration (EM) is one of the major reliability issues for metal interconnect in integrated circuits (ICs). The ever increasing complexity of interconnects requires more demanding reliability of each component.

The prime interest of this work is to investigate the EM failure physics for submicron Cu interconnections based on driving force approach including the effect of surrounding materials. For EM in interconnect, there are various extrinsic weaknesses which are having significant impact on failure characteristics. One good example of extrinsic weakness is stress gradient which exists in the interconnect core material due to thermo-mechanical mismatch at typical EM test condition.

From the very beginning of the EM history, the electron wind force (EWF) is believed to be the most responsible driving force for atom or vacancy migration, although it is well known that the surrounding materials and the interconnect processing history highly influence the failure mechanisms. Apart from the EWF, the other driving forces such as forces from stress gradient, temperature gradient, surface tension etc. are believed to be only modify the atomic flux (AF) and corresponding atomic flux divergence (AFD) created by EWF.

It is the purpose of this study to verify that the above mentioned forces can act as potential driving force in EM. The obvious sources of AFDs are the non-uniform distributions of current density, temperature, and stress fields in the metallization. These non-uniformities arise due to the presence dissimilar materials surrounding the

metallization and hence responsible for various extrinsic weakness against EM mass transport.

In investigating the EM failure physics, the key reliability process parameters are identified to improve the EM reliability. In order to investigate the various driving forces and their effects on EM reliability for submicron interconnects, AFD based model is developed using finite element method. By introducing the above mentioned combined driving force approach and conducting EM experiments for submicron Cu interconnects, various EM characteristics are described.

The model predicts that the stress free temperature (SFT) is one of the important process-related parameter that influences interconnect EM reliability. It is also predicted that by lowering the SFT, EM life-time can be improved, which is verified by conducting EM experiments.

In order to obtain critical void volume, resistance change profile etc., a dynamic EM model is described for submicron Cu dual damascene (DD) line-via test structure. The model predictions are found to agree well with experimental results.

One of the EM reliability concern is the current crowding in line-via interconnects. The effect of current crowding is described in the light of width dependence and EM failure characteristics. A modified Black's equation is prescribed for line-via interconnects in the presence of current crowding.

In short, it is realized that there are several extrinsic factors that influence the EM failure characteristics significantly. The contribution of AFD from various

sources of driving force to the total AFD at various phase of EM failure process is described. It is shown that at the very beginning of EM failure process, like in the phase of void nucleation, stress gradient induced driving force dominates while in the later part of the failure process like in phase of void growth, the EWF dominates. It is identified that the SFT, temperature gradient, current crowding etc. have paramount impact on EM failure process and reliability. Few methods are proposed to improve the interconnect EM life-time.

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Chapter 1

INTRODUCTION

1.1 Motivation

EM remains an attractive research topic from 1980s. Since 1970 the major failure in discrete solid state devices and integrated circuits is EM. EM describes diffusion-controlled mass transport in metallic materials that is driven by the application of electric current. The physical models have not changed significantly since 1980 and are still based on the magnitude of electric field, grain boundary diffusivity or interface diffusivity, and grain boundary structural factors that determine atomic flux distribution and distribution of flux divergence. The mass accumulation and depletion caused by the non-uniform flux directly influences the metallization resistance and current density distribution.

Although Cu is very attractive interconnect material and is actively explored during the last several years, only recently it is demonstrated as a feasible production technology. The efforts to implement Cu interconnects is accelerated after IBM's and Motorola's announcements in 1997 to integrate Cu in CMOS technology. Although Cu has lower resistivity and better reliability than Al alloys, it is not used in silicon

ICs until very recently because of processing difficulties and device contamination issues.

To ensure the interconnect reliability; industry is continuing its relentless effort in the EM study of Cu. The ever increasing complexity of interconnects requires more demanding reliability of each component. The limiting factor in interconnect reliability is increasingly dominated by the EM performance of vias with the performance of lines playing a substantially lesser role in submicron technology. The transition from Al interconnects to Cu leading to new via structure fabricated by dual damascene process and EM failures are significantly different in such structure.

The possibility of existence of various driving forces in EM was identified in the late 1960's [1]. Soon after the discovery of EM, "electron wind" and "direct force" were taken as the main sources of driving forces in EM [1-5]. The atomic flux was estimated from the resultant force of these two driving forces [6-7].

In 1969, the "thermomigration" is reported to be as one of the potential driving forces in EM [8]. Subsequently, experimental and theoretical works were presented in the support of "thermomigration" as a driving force in EM [9-13]. It was understood that this driving force arises through the presence of temperature gradient in the metallization.

Though the diffusion of vacancies under stress gradient was reported in the 1957 [14], the stress gradient was identified as one of the potential driving forces in EM around the late 1970 [7,15-18]. Thermo-mechanical mismatch between

interconnect and its surrounding materials is one of the prime source of stress gradient in the interconnection [17-21]. Another source of stress gradient is the EM induced stress, especially when the interconnect length is short ($\sim 30 \mu\text{m}$) [15-17].

Later on, it was shown that surface tension may also induce driving force during EM [22-24]. It was also shown that surface tension induced driving force is important to describe void shape and size [22-24].

Although the influence of above-mentioned driving forces in EM was known, a combined model considering the potential driving forces were not reported until 1999 [25]. These combined models were on Al-based metallization and strengthen the understanding of EM physics of Al interconnects [25-26]. Despite of significant difference in the EM of Al and Cu [27-28] and the technological move towards the submicron Cu-DD-Technology, combined driving force models for Cu-based interconnect would be useful to give insight of the underlying EM physics for Cu-based interconnections and their reliability. It is a natural question how the EM characteristics changes under the influence of surrounding materials and their processing history.

Furthermore high temperature gradient exists in interconnects at EM test condition, especially for submicron technology. Hence, it is necessary to investigate the driving force from temperature gradient and corresponding atomic flux and atomic flux divergence.

The non-uniform stress is another factor that contributes as a driving force during EM mass transport. The residual stress also plays an important role in EM failure. Due to the complex geometry of interconnect structure, stress gradient in the interconnect core material must exist. At elevated temperature during EM test, the structure must get deformed due to the dissimilar material properties of multi-layer structure.

Thus it is necessary to understand the EM failure physics in the light of driving force approach especially, for Cu DD interconnects. The driving force approach must highlight the atomic flux and atomic flux divergence from the different sources of driving forces to identify the key parameters in processing and reliability to improve the EM life-time.

Finite element analysis (FEA) can be used to model the EM performance. ANSYS® is one of the promising software tools, which can be used for modeling. This software has the ability of handling unlimited “elements” and “nodes” in the scheme of finite element model and therefore precise modeling can be obtained. The aim is to integrate the various driving forces and processing parameters into the model and to verify the influence of these parameters on the EM performance of submicron Cu interconnects.

1.2 Objectives

The main objectives of this thesis work are as follows:

- 1) Developing atomic flux divergence (AFD) based model combining various driving forces in EM.
- 2) Study the various driving forces at EM test condition and their contribution to total AFD.
- 3) Identifying the key process parameters to improve the EM interconnect reliability.
- 4) Study the impact of the SFT in EM failure characteristics and corresponding influence on AFDs.
- 5) Study EM degradation process and AFD variations during EM degradation.
- 6) Study of current crowding effect.

1.3 Contribution of the Thesis

This thesis work is aimed for Cu-based metallization. The major contribution of the thesis covers four aspects:

- 1) Various driving forces in EM are compared. Stress gradient induced driving force and temperature gradient induced driving force are found to be contributing to the total AFD. A combined driving force model (CDFM) is developed.
- 2) Mathematical model combining various driving forces is developed for EM. The model agrees well with experimental results for both line and line-via EM. A modified Black's equation is derived for line-via EM. The effect of current crowding is also described.

- 3) SFT is identified to be one of key process parameter that influences the EM reliability. It is shown by modeling that by reducing the SFT, EM life-time can be improved. The model predictions agree well with the experiments conducted on submicron Cu DD line-via structure.
- 4) A dynamic model to study EM degradation is implemented. This model consists of various driving forces. The model predicts many interesting facts such as stress gradient induced driving force and EWF dominates at the beginning and later part of EM voiding respectively.

1.4 Organization of the Thesis

The thesis contains seven chapters. Chapter one is the introduction of the thesis, including motivation, objectives, contribution and organization. The literature reviews on EM driving forces are presented in chapter two. Chapter three presents the modeling description and the comparison of AFs from EWF, stress gradient induced driving force, temperature gradient induced driving force and surface tension induced driving force. In this chapter modeling and experiments on submicron Cu line interconnects are also presented. Chapter four is devoted to the work in EM failure characteristics of submicron Cu line-via structure for different SFTs, including introduction, modeling and experiments. The EM degradation modeling including experiment is presented in chapter five. The effect of current crowding on EM including, modeling and experiments is presented in chapter six. Finally, chapter seven summarizes the results of this work and gives recommendation for future work.

Chapter 2

LITERATURE REVIEW

2.1 Electromigration

2.1.1 Introduction

EM is a mass transport phenomenon under electrical driving force. Thus the process is characterized as an atomic diffusion process. Commonly it is believed that electron wind force (EWF) is the main driving force that causes EM in metallic conductor. However, apart from the EWF, there are several kinds of driving forces that may arise at typical accelerated EM test condition. In fact in 1974, *Huntington* mentioned “There are many kinds of driving forces that can bias atom motions in the solid phase” [1]. In this chapter various driving forces in the EM will be reviewed based on the published literature. The various driving forces and their impact on EM will also be addressed.

2.1.2 Driving forces in EM

In EM, the driving force is the force responsible for displacement of atoms and vacancies through diffusion process. Hence, driving force is the cause of mass

transport in EM. When the mass transport in interconnect is significant due to the EM, the interconnect may fail by formation of voids and hillocks. Atomic unit is commonly used for the unit of driving force. However, for ease of computation, SI unit of force is used for all the driving forces in this thesis.

Traditionally in the theory of EM, driving force contains two components. These are so called “wind force” ($\vec{F}_{wd}$) and the “direct force” ($\vec{F}_d$). The “wind force” is the force exerted by the bare ions due to the momentum exchange from the moving electron when electric current is applied. On the other hand “direct force” is the electrostatic force on the ions due to application of electric field. The direction of “direct force” is opposite to the direction of “wind force”. The “wind force” acts along the electron flow, whereas the direct force acts along the direction of electric field (opposite to the direction of electron flow). The resultant force is given by [1-3]

$$\vec{F}_{em} = \vec{F}_{wd} + \vec{F}_d \quad (2.1)$$

For very high current density ($\sim 1 \text{ MA/cm}^2$) as in the case of real interconnect, the electron moves with very high speed ($\sim 10^6 \text{ m/sec}$) [3] and higher momentum is transferred to ions. The result is appreciable atomic transport in the direction of electron flow (in many metals like Cu, Al), which is known as “Electromigration”. Thus in the EM of the metals like Cu or Al, the “wind force” dominates over the “direct force”. With non-zero atomic flux divergence, there will be either a mass depletion (divergence > 0) or accumulation (divergence < 0), leading to formation of voids or hillocks. This theory was developed by *Fiks* and *Huntington* [1-5] in the early 1960’s and is known as the ballistic model of EM.

The interaction between the current carrying electrons and the migrating ions was described by scattering of defects in the ballistic model of EM. The model assumes that the “wind force” on a lattice defect is given by the momentum transfer by the electrons per unit time as they scattered by the defect. Taking m_0 is the electronic mass; the momentum transfer to the electrons is given by the m_0 times the group velocity of Bloch wave. The x-component of the momentum transferred per unit time per unit volume to the defects is given by

$$\frac{dM_x}{dt} = \left(\frac{1}{4\pi^3} \right)^2 \iint (m_0 / \hbar) \left(\frac{\partial \zeta}{\partial k'_x} - \frac{\partial \zeta}{\partial k_x} \right) f(\vec{k}) [1 - f(\vec{k}')] W_d(\vec{k}, \vec{k}') d\vec{k} d\vec{k}' \quad (2.2)$$

where, ζ is the electronic energy, $W_d(\vec{k}, \vec{k}')$ is the transition probability per unit time that the electron in state $\vec{k}$ will jump to state $\vec{k}'$ by virtue of its interaction with point defects, $f(\vec{k})$ is the electron distribution and $\hbar$ is the Planck constant. By interchanging primed and unprimed variable of integration, Eq. (2.2) takes form

$$\frac{dM_x}{dt} = \left(\frac{1}{4\pi^3} \right)^2 \iint (m_0 / \hbar) \frac{\partial \zeta}{\partial k_x} \{ f(\vec{k}) [1 - f(\vec{k}')] W_d(\vec{k}, \vec{k}') - f(\vec{k}') [1 - f(\vec{k})] W_d(\vec{k}', \vec{k}) \} d\vec{k} d\vec{k}' \quad (2.3)$$

which can be further simplified by introducing a relaxation time τ_d , defined by

$$\frac{f(\vec{k}) - f_0(\vec{k})}{\tau_d} = \int \{ f(\vec{k}) [1 - f(\vec{k}')] W_d(\vec{k}, \vec{k}') - f(\vec{k}') [1 - f(\vec{k})] W_d(\vec{k}', \vec{k}) \} d\vec{k}' / 4\pi^3. \quad (2.4)$$

Here $f_0(\vec{k})$ denotes the equilibrium electron distribution. Since, a unique τ_d is independent of $\vec{k}$ in metals; the substitution of Eq. (2.4) into Eq. (2.3) gives

$$\frac{dM_x}{dt} = \frac{m_0}{\tau_d \hbar} \int \frac{\partial \zeta}{\partial k_x} f(\vec{k}) d\vec{k} / 4\pi^3. \quad (2.5)$$

The current density in the x-direction j_x can be expressed as

$$j_x = \frac{-e}{4\pi^3} \int f(\vec{k}) \frac{\partial \zeta(\vec{k})}{\hbar \partial k_x} d\vec{k} \quad (2.6)$$

(e represents the electronic charge) and it follows that

$$\frac{dM_x}{dt} = -\frac{j_x m_0}{e \tau_d} \quad (2.7)$$

Assuming that the effect of this rate of momentum transfer forms a continuous force to each defect, then the force field can be estimated as

$$F_x = -\frac{j_x m_0}{e \tau_d N_d} \quad (2.8)$$

where N_d is the density of defects. The contribution of the defects to the resistivity be $\rho_d = m_0 / N_e e^2 \tau_d$, where N_e is the density of conduction electrons and m^* is their effective mass, the force is given by

$$F_x = \frac{-N_e |e| j_x \rho_d m_0}{N_d |m^*|} = -|e| Z E_x \frac{N \rho_d}{N_d \rho} \frac{m_0}{|m^*|} \quad (2.9)$$

where, Z is the valence of metallic atom, E_x is the x-component of the electric field and N is the atomic density. Due to the small difference between m_0 and $|m^*|$, the “wind force” can be rewritten as

$$\vec{F}_{wd} = -|e| Z \vec{E} \frac{N \rho_d}{N_d \rho}$$

where ρ is the resistivity. On the other hand the direct force is given by

$$\vec{F}_d = Z_d^* |e| \vec{E} \quad (2.10)$$

where, Z_d^* is a parameter related to valence of the metallic atom. In the absence of scattering process, Z_d^* is the valence (Z) of the metallic atom. Thus the total force is given by

$$\vec{F}_{em} = \left(Z_d^* - Z \left[\frac{\rho_d}{N_d} \right] \left[\frac{N}{\rho} \right] \right) |e| \vec{E} \quad (2.11)$$

The resultant force given by Eq. (2.11) can be simplified as:

$$\vec{F}_{em} = Z^* |e| \vec{E} \quad (2.12)$$

$$\text{where, } Z^* = Z_d^* - Z \left[\frac{\rho_d}{N_d} \right] \left[\frac{N}{\rho} \right] \quad (2.13)$$

and is called the “effective charge number”.

For simplicity, the resultant force as given by Eq. (2.12) will be termed as “electron wind force” (EWF) in the rest of this thesis.

The EM drift velocity is given by Nernst-Einstein equation as:

$$\vec{v}_d = D \frac{\vec{F}_{em}}{k_B T} \quad (2.14)$$

where, the atomic diffusion coefficient is given by

$$D = D_0 \exp\left(-\frac{E_a}{k_B T}\right) \quad (2.15)$$

where, E_a is the activation energy associated with the diffusion process, k_B is the Boltzmann’s constant, D_0 is the diffusivity pre-factor and T represents the temperature.

Using equations (2.14), (2.12) and (2.15), the drift velocity can be expressed as:

$$\vec{v}_d = \frac{D_0}{k_B T} |e| \cdot \rho \cdot Z^* \cdot \vec{j} \cdot \exp\left(-\frac{E_a}{k_B T}\right). \quad (2.16)$$

The drift velocity given by Eq. (2.16) is more commonly expressed as:

$$\vec{v}_d = \frac{D_{eff}(T)}{k_B T} \cdot (Z_{eff}^* \cdot e \cdot \rho \cdot j) \quad (2.17)$$

where, $D_{eff} \times Z_{eff}^* = D_b Z_b^* f_b + D_p Z_p^* f_p + D_i Z_i^* f_i + D_s Z_s^* f_s + D_{gb} Z_{gb}^* f_{gb}$.

The subscripts represent the various diffusion paths. These diffusion paths are

b = Bulk

p = Pipe

i = Interface

s = Surface

gb = Grain-boundary

And $f_r (r = b, p, i, s, gb)$ is the fraction of atoms diffusing through a given path way;

it depends on the geometry of the interconnect used for the EM test. Thus the atomic

flux ($\vec{J}_1$) from EWF can be expressed as [6-7]:

$$\vec{J}_1 = \vec{v}_d \times N = \frac{N}{k_B T} e Z^* \vec{j} \rho D_0 \text{Exp}\left(-\frac{E_a}{k_B T}\right). \quad (2.18)$$

Each pathway is anticipated to have different Z^* component because the wind force varies according to local electronic environment surrounding a given atom. As contributions due to b, p are small ($< 400^\circ\text{C}$), only i, gb, s paths arise during the typical EM failure process.

The ballistic model of the EM as discussed above is the simplest theory that found to be controversial and many other interacting driving forces are identified in EM which will be discussed in subsequent sections. Though there is a significant

improvement in theoretical understanding to date, Eq. (2.17) is still employed for the basis of experimental studies on the EM.

Besides the EWF, other components of the EM driving force basically all results from the inhomogeneities caused by structural or the EM-induced damage itself. The sources of these driving forces are temperature gradient [1, 8-13], stress gradient [1, 6-7, 14-20] etc. The impact of these driving forces on atoms/vacancies is schematically shown in Figure 2.1. Later on, driving force from surface tension (also known as surface migration) is also taken into account in EM failure process, especially in describing the void shape and size [21-24]. The origin and impact of these driving forces are described in the next sections.

FIG. 2.1: Schematic representations of (a) EWF, (b) stress gradient and (c) temperature gradient on atoms/vacancies.

2.1.2.1 Sources of stress gradient induced driving force

Broadly there are two sources of stress gradient which may influence the EM failure in metal interconnect. The first source is the non-uniform stress that arises due to thermo-mechanical mismatch of the metallization material with surrounding materials at EM test condition [17-20]. This type of stress gradient in the test structure arises from the very beginning of the EM test and is relieving only after void formation.

The second source is the EM induced non-uniform stress along the interconnect length [14-16]. This type of stress gradient increases ideally from zero value with the EM test time until failure. The typical order of stress gradient that exists in the metallization during EM can be as high as 10^{14} Pa/m.

2.1.2.2 Evidences of stress gradient induced driving force

The role of stress gradients as a driving force in EM was first explored in a series of experimental and theoretical works in the 1970s by *Blech* and co-workers [7,15,16]. A series of EM experiments were conducted and it is observed that, after a period of time, the metal line becomes shorter as a result of cathode end removal in the direction of electron flow. The anode edge eventually produced hillocks or extrusions to accommodate the material removed from the other edge.

It was interpreted that during the EM, stress gradient will increase until a steady state condition is achieved, when two forces are equal and opposite and mass flow will stop. When the steady state is achieved, if the maximum stress at the cathode

end is less than the maximum stress that can be accommodated without formation of any voids/hillocks, resultant mass flow ceases and the effect of EM is absent. On the other hand, if the stress at the cathode end is greater than this, the mass flow will continue towards the anode end from cathode end. Since the EM induced stress gradient depends on the interconnect length, there exists a critical length below which EM failure is not observed.

For further clarification on the stress gradient generation as a function of interconnect length at EM test condition, *Korhonen et al.* [29] presented a rigorous theoretical investigation. Although this interpretation well describes the Blech length effect in EM, the sources of EM induced stress gradient is not considered for longer interconnect and the Eq. (2.17) is still used today in EM experiments [30-35]. A recent edge displacement experiment on Cu based metallization also does not support the hypothesis of back flow during EM [36]. This is due to the lack of experimental evidence on in-situ stress measurement at various distances along the length of interconnect as a function of time. Thus it is commonly accepted that, the shorter lines do not fail due to lack of sufficient defects present in interconnect.

On the other hand, it was anticipated that the stress gradient due to thermo-mechanical mismatch could influence the EM performance decade ago [17]. It was shown that the EM-induced failure is significantly due to thermo-mechanical mismatch.

In a previous report [37], it was shown that the interconnect EM failure time strongly depends on the passivation layer thickness and it was concluded that the

observed failure time variation is due to the variation of thermo-mechanical stress for various passivation layer thickness.

On the other hand, it was understood that due to the high processing temperature (about 400°C) during the interconnect fabrication the metallization remains in tensile stress state at EM test condition. The source of this thermo-mechanical stress is nothing but due to the thermo-mechanical mismatch of the interconnect material with the surrounding dielectric. One therefore, expects by lowering the processing temperature, EM life-time could be improved. In a subsequent work [38], *Lloyd* and co-workers studied interconnect EM performance for different lot with different processing temperature. They found about five times better EM life-time by reducing the dielectric deposition temperature from 390 to 325°C on the interconnect lines. This tremendous improvement in EM performance is noticed due to the reduction of tensile stress gradient that exists in interconnect at typical EM test condition. However, further reduction in processing temperature such as 250°C was not advised. This is because of the poor quality of the dielectric when deposited at such low temperature.

Later on *Lloyd* reviewed the effect of mechanical stress on EM [21]. It was established that the thermo-mechanical stress can be as high as EM induced stress and if this thermo-mechanical stress is not taken into account, the failure time will be overestimated [21].

Apart from the above mentioned evidences of stress gradient induced driving force on Al-based interconnect, recently similar observations is found for Cu-based

metallization. In order to compute the stress gradient due to thermo-mechanical mismatch, one needs to know about the interconnect stress free temperature (SFT). Ideally SFT is the temperature at which the metallization remains free from stress and strain. This temperature exists due to the various degrees of thermal processes during sample fabrication. The SFT mainly depends on the dielectric/cap layer deposition temperature and final annealing temperature. The SFT of Cu-based interconnect is reported to be in the range of 350 to 400°C [39-41], depending on metallization process or annealing temperature. At typical accelerated EM test condition, the metallization temperature remains below the SFT and thus tensile stress exists in the metallization. The non-uniformity of this stress state arises from many sources: e.g. due to the complex interconnect geometry, non-uniformity of temperature distribution, involvement of several surrounding materials etc. One can expect highly non-uniform stress field near the corner and edges of interconnects and these are the zones where different materials meet together and influence each other. Thus this type of stress gradient produces very high local effect during EM test.

In order to take account the SFT and the impact of stress from surrounding materials, a correction factor to the activation energy was proposed recently [42]. The impact of stress due to surrounding material is expected to be more serious when Cu lines are integrated with low-k dielectric. In such a situation it was shown to follow non Arrhenius relation when the SFT and thermo-mechanical stress is not taken into account in the EM characteristics [43]. This is due to high thermo-mechanical mismatch due to presence of the low-k material as dielectric. Because of this reason the traditional way of estimating activation energy may result a negative value which is not possible physically [43].

2.1.2.3 Summary on stress gradient induced driving force

From the above mentioned discussion, the impact of stress gradient induced driving force on EM is summarized as follows:

1. Due to the presence of thermo-mechanical stress, the interconnect fails faster than the expected failure time.
2. During EM, due to the existence of thermo-mechanical stress, the stress in the interconnect reaches to the critical stress (required for voiding) in shorter time than the expected time and as a consequence, the failure time becomes shorter than the expected failure time.
3. Unlike EM induced stress gradient, which is along the length of interconnect, the thermo-mechanical stress gradient is not like that. It acts any where in interconnect and favors EM damage to grow faster, whereas EM induced stress gradient acts against the EWF and delays the EM failure to occur. Thus it can be predicted that void begins due to thermo-mechanical stress gradient and the atoms are driven by EWF [17].
4. The driving force that arises from thermo-mechanical mismatch acts from the very beginning of EM test and is relaxed during void formation.
5. It is necessary to compare the stress gradient induced driving force with EWF.
6. It is not understood how stress gradient induced driving force from thermo-mechanical stress can generate AFD. The contribution of this AFD is also not compared with that of from EWF.
7. It is also not understood how to take account the impact of stress gradient induced driving force in the EM failure characteristics.

2.1.2.4 Sources of temperature gradient induced driving force

Atoms have tendency to move from high temperature to low temperature area (see Figure 2.1 (c)), and thus temperature gradient creates atomic flow which in turn induces driving force. There are many ways by which the EM test sample experiences temperature gradient. The simplest source is the Joule heating which causes temperature gradient at the interconnect surfaces. This type of temperature gradient exists before the EM effect takes place and increases with time in vicinity of voids and hillocks; and cannot be avoided totally in principle, but would be possible to minimize. During the EM voiding, local Joule heating increases which in turn increases the temperature gradient.

There is also structurally induced temperature gradient. For example, a test line connected by via must have different temperature locally, since via portion acts as good heat conductor instead of heat generator. As a result of structurally induced temperature gradient, hot spot arises in interconnect and again as before this type temperature gradient arises at the very beginning of the EM test. The thickness variation of the dielectric/substrate below the test interconnect or the line width/thickness variation along the length of the test interconnect etc. are the other obvious sources of temperature gradient.

It is therefore necessary to take account temperature gradients and their corresponding AFD during the EM failure process.

2.1.2.5 Evidences of temperature gradient induced driving force

Temperature gradient is an important source of AFD, since the AF depends exponentially on temperature. There are some early evidences where it was shown that the AFD occurs solely due to the initial temperature gradient [12,44-46]. For example, at 200°C in aluminum, a 5°C change in temperature results in a change of more than 10% in the EM flux. Experimentally it was shown that voiding occurs in the regions where electron flows in the direction of increasing temperature, and hillocks form in locations where electron flows in the direction of decreasing temperature [47].

Temperature gradient dependence of EM failure was confirmed by *Lloyd* [13] and *Schwarzenberger* [48] and their coworkers. They observed that EM failure location was typically nearer to the maximum temperature gradient; on the other hand the location of non-temperature-gradient induced failure was observed to be distributed randomly.

Further evidences on temperature gradient induced driving force were reported by *Weiling* et al. [49-50]. They performed EM experiments on Al-based metallization with built-in heating element to intentionally produce a temperature gradient along the metal line and observed that the median-time-to-failure (MTF) improved if the temperature gradient is such that the electron flow is in the direction of increasing temperature. The void locations in this case are the same as that in the initial stage of the slowly increasing resistance. A significant drop in the MTF was also noticed for the case of temperature gradient in opposite direction. The above mentioned observations are also supported by *Jonggok* et al. [51].

Nguyen et al. [52] performed similar experiments with built-in heating element in the EM test structure. From their experiments, they found that the time to failure with temperature gradients of 0.09, 0.19, and 0.28 K/ μm were reduced to 90%, 40% and 9% of the time to failure without temperature gradient respectively. They also observed that the voids occur near the site of maximum temperature gradient, and it is consistent with the physical model developed by *Ru* [53].

Recently for Cu-based metallization, *Arnaud* et al. [35] observed higher density of voids in the region of large temperature gradient that exists in the metallization due to the application of EM stress. *Wang* et al. [54] also reported that the temperature gradient doubles the flux divergence near the edges of modern interconnect.

2.1.2.6 Summary on temperature gradient induced driving force

With above mentioned experimental evidences, the impact of temperature gradient induced force on the EM is summarized as follows:

1. The temperature gradient in interconnect may act as a driving force in the EM.
2. The existence of non-uniformity in the temperature field in interconnect during the EM test (without any additional heating element) may also act as a driving force.

3. Since, the temperature gradient induced driving force is proportional to the temperature gradient, the available heat dissipation path play an important role. Therefore, the interconnection design and geometry have great impact on temperature gradient induced driving force.
4. With proper interconnect design, it might be possible to improve interconnect life-time, since it was shown experimentally that the temperature gradient induced driving force may act in the opposite direction of the EWF.
5. It is understood that local temperature gradient induced driving force near the void will increase from its initial value due to existence of highly non-uniform temperature field in the vicinity of void.
6. Typically, temperature gradient induced driving force is higher near the edges and surfaces, facing dissimilar materials.

2.1.2.7 Sources of surface tension induced driving force

The surface tension induced driving force arises mainly from three sources. First source is obviously the presence of microscopic structural variation in the interconnect surfaces. Interconnect surface roughness is thus the primary source of surface tension induced driving force. The second source is the grain boundary surfaces. And the third source is the presence of void near the void vicinity. The driving force arises to minimize the energy from the surface tension.

2.1.2.8 Evidences of surface tension induced driving force

It is shown that surface tension induced driving force is important to the EM. This force is described to dominate, once the void nucleation occurs. *Arzt and Kraft et al.* [22,24] studied the effect of surface tension on the EM failure mechanisms. They proposed that surface tension plays a significant role in void shape change. The void shape appears to be rounded wedge-like if the surface diffusion is sufficiently higher compared to the same from EWF. And under an opposite situation, the voids exhibits narrow crack-like shape [55-56]. *Wang et al.* [23] observed various types of EM void shape and these observations are correlated by considering surface tension induced driving force as one of the driving force along with the EWF.

2.1.2.9 Summary on surface tension induced driving force

With the above mentioned evidences, the impact of surface tension induced driving force on the EM is summarized as follows:

1. This force is significant only in the presence of void.
2. This force plays role on void evaluation and void shape.
3. This force may not be significant at the very beginning of the EM and thus does not play role in void nucleation.

Chapter 3

A COMBINED DRIVING FORCE MODEL

3.1 Introduction

In this chapter various driving forces are computed and their magnitudes are compared with EWF. The mathematical formulations for computing AFDs are presented. In this way important driving forces are predicted. Coupled field analysis by coupling current, temperature and stress fields and combining the important driving forces, an AFD based model is developed. This model will be termed as ‘combined driving force model’ (CDFM) in this thesis.

Successful applications of the CDFM into the line EM and line-via EM for submicron Cu damascene interconnections are presented. The model predictions are found to agree well with experimental results. A special application of the model to explain the asymmetric nature of EM characteristics in the case of line-via interconnection is also presented.

3.2 Significance of various driving forces in the EM mass transport

3.2.1 Significance of stress gradient induced driving force

In this section AF from stress gradient induced driving force in EM will be estimated and compared with that of EWF. The atomic flux from stress gradient induced driving force, ($\vec{J}_2$) can be expressed as [6-7]

$$\vec{J}_2 = \frac{N\Omega D_0}{k_B T} \text{Exp}\left(-\frac{E_a}{k_B T}\right) \nabla \sigma_h \quad (3.1)$$

where, Ω is the atomic volume and σ_h is the hydrostatic stress in the conductor.

In order to obtain a rough estimation on the diffusive flux originating from the stress gradient due to thermo-mechanical mismatch, one can proceed to evaluate the expression given by Eq. (3.1) as follows. The hydrostatic stress in Cu film surrounded by SiO₂ can be estimated as

$$\sigma_h \sim \frac{Y}{1-\nu} (CTE_{eff}) (\Delta T)$$

where, Y (Young's modulus) ≈ 129.8 GPa for Cu, ν (Poisson ratio) ≈ 0.339 for Cu, CTE_{eff} (difference in the temperature co-efficient of expansion with surrounding material) $\approx (16.5 - 0.68) \times 10^{-6}$ (/°C) $\approx 15.82 \times 10^{-6}$ /°C and $\Delta T \approx$ (SFT – Metallization temperature) $\approx 50^\circ\text{C}$. Thus the hydrostatic stress in Cu comes out to be, $\sigma_h \sim 155.3$ MPa. Similarly, the magnitude of hydrostatic stress in SiO₂ can be computed (with $Y = 71.4$ GPa, $\nu = 0.16$) and it is found to be ~ 67.2 MPa. The parameters for material

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properties are taken from the ref. [57]. Thus the stress gradient (stress in SiO₂ is compressive),

$$\nabla \sigma_h \sim \frac{\sigma_h|_{Cu} - \sigma_h|_{SiO_2}}{1\mu m} \sim \frac{(155.3 + 67.2)}{1 \times 10^{-6}} \text{ (MPa/m)} \sim 222.5 \times 10^{12} \text{ Pa/m.}$$

Using the above value, the flux expressed by Eq. (3.1) can be estimated as (in SI unit)

$$\begin{aligned} \bar{J}_2 &= \frac{N\Omega D_0}{k_B T} \text{Exp}\left(-\frac{E_a}{k_B T}\right) \nabla \sigma_h \\ &\approx \frac{(8.44 \times 10^{28}) \times (1.18 \times 10^{-29}) \times (7.8 \times 10^{-5})}{(1.386 \times 10^{-23}) \times (300 + 273)} \left[\text{Exp}\left(-\frac{0.8}{8.6 \times 10^{-5} \times (300 + 273)}\right) \right] \times 222.5 \times 10^{12} \\ &\approx 1.9 \times 10^{23} \text{ number/m}^2\text{-sec.} \end{aligned}$$

In order to compare the magnitudes of atomic fluxes (AFs), one might be interested to compute the ratio of J_2/J_1 . After simplifying, this ratio (r_{21}) comes out to be (J_1 is expressed by Eq. 2.18 in chapter 2)

$$r_{21} = \frac{J_2}{J_1} = \frac{\Omega \cdot \text{grad} \sigma_h}{eZ^* j \rho} \quad (3.2)$$

Putting typical order of magnitudes of the parameters involved in equation (3.2), one can get (the value of the parameters are taken from ref. [57])

$$r_{21} \approx \frac{10^{-29} m^3 \times \frac{10 \text{ MPa}}{10^{-6} m}}{10^{-19} C \times 10^1 \times 1 \text{ MA} / cm^2 \times 10^{-8} \Omega \cdot m} \approx 1 \quad (3.3)$$

It is commonly understood that stress gradient induced driving force only modifies the existing EWF during EM. However, typical value of r_{21} as obtained

above implies that one cannot ignore the impact of AF that arises from stress gradient during EM, concluding that stress gradient induced driving force not only modify the EWF, but it may act as a potential driving force during EM.

3.2.2 Significance of temperature gradient induced driving force

In this section temperature gradient induced driving force in interconnect that arise during EM test will be examined. The AFs from temperature gradient induced driving force and EWF will be compared. The AF from temperature gradient induced driving force, ($\bar{J}_3$) can be expressed as [9,11-12]:

$$\bar{J}_3 = -\frac{NQ^*D_0}{k_B T^2} \text{Exp}\left(-\frac{E_a}{k_B T}\right) \nabla T \quad (3.4)$$

The ratio (r_{31}) of magnitudes of AFs from temperature gradient induced driving force to EWF comes out to be (the value of the parameters are taken from ref. [57] and see Eq. 2.18 in chapter 2 for the expression of J_1)

$$r_{31} = \frac{Q^*(\nabla T)}{eZ^*j\rho T} \approx \frac{10^{-1} \text{ eV} \times 1 \text{ K} / \mu\text{m}}{10^{-19} \text{ C} \times 10^1 \times 1 \text{ MA} / \text{cm}^2 \times 10^{-8} \Omega \cdot \text{m} \times 573 \text{ K}} \approx 1 \quad (3.5)$$

Typical value of r_{31} , as obtained above indicating that temperature gradient induced driving force cannot be ignored in comparison to EWF. Microscopic temperature gradient may get value much higher than the value used in the above equation. And in the case of void vicinity, the temperature gradient could be higher by

an order of magnitude. Thus in principle, temperature gradient induced driving force is expected to contribute to the resultant AF.

3.2.3 Significance of surface tension induced driving force

The AF from the surface tension can be expressed as [23]:

$$\bar{J}_4 = \frac{D_0}{k_B T} \exp\left(-\frac{E_a}{k_B T}\right) \gamma_s \frac{d\kappa}{dl} \quad (3.6)$$

where, γ_s is the surface energy, κ is the radius of curvature and l is the length.

The ratio (r_{41}) of AFs from surface tension induced driving force to EWF comes out to be (the value of the parameters are taken from ref. [57] and see Eq. 2.18 in chapter 2 for the expression of J_1)

$$r_{41} = \frac{\gamma_s \frac{d\kappa}{dl}}{NeZ^* j\rho} \approx \frac{1J/m^2 \times (10^{-6}m)^{-2}}{10^{29}(m^3)^{-1} \times 10^{-19}C \times 10^1 \times 1MA/cm^2 \times 10^{-8}\Omega.m} \approx 10^{-1}$$

Since, the above ratio comes out to be one order less; the surface tension induced driving force may not be a significant driving force in the EM. In the above calculation, the value of the term $\frac{d\kappa}{dl} \approx \frac{1}{(1\mu m)^2}$ is taken from observed void shape.

The numerator in the expression of r_{41} is evaluated from the work presented in ref. [23]. In the absence of void, ideally the numerator is nothing but zero. Thus in the

worst case scenario, the AF from surface tension induced driving force is one order lesser in magnitude than that of EWF and is zero in the absence of void. It is therefore reasonable to ignore surface tension induced driving force while integrating other driving forces.

It is to be noted here that the EM can also be treated as a phenomenon of the thermodynamics of irreversible process [25,58]. In this formalism, various types of potentials (electrical, mechanical etc.) and their gradients are considered. However, when AF expressions are derived from the above formalism, equations (2.18), (3.1), (3.4) and (3.6) are reproduced [25,58]. The irreversible property of the EM is useful in the modeling of interconnect degradation or void evolution during EM mass transport.

3.3 Model generation

In this section, the description of the CDFM is presented. As discussed in earlier sections, EWF, stress gradient induced driving force and temperature gradient induced driving are the three driving forces which are comparable to each other and can be significant in the EM failure process. Hence in the rest of this thesis only these three forces are considered. The AFs from EWF, stress gradient induced driving force and temperature gradient induced driving force are expressed earlier by the expressions (2.18), (3.1) and (3.4) respectively. The AFD from these driving forces can be expressed respectively as [26,59-60]:

$$\text{div}(\vec{J}_1) = \left(\frac{E_a}{k_B T^2} - \frac{1}{T} + \alpha \frac{\rho_0}{\rho} \right) \cdot \vec{J}_1 \cdot \nabla T \quad (3.7)$$

$$\text{div}(\vec{J}_2) = \left(\frac{E_a}{k_B T^2} - \frac{3}{T} + \alpha \frac{\rho_0}{\rho} \right) \cdot \vec{J}_2 \cdot \nabla T + \frac{NQ^* D_0}{3k_B^3 T^3} j^2 \rho^2 e^2 \exp\left(-\frac{E_a}{k_B T}\right) \quad (3.8)$$

$$\begin{aligned} \text{div}(\vec{J}_3) = & \left(\frac{E_a}{k_B T^2} - \frac{1}{T} \right) \cdot \vec{J}_3 \cdot \nabla T + \frac{2YN\Omega D_0 \xi}{3(1-\nu)k_B T} \exp\left(-\frac{E_a}{k_B T}\right) \left(\frac{1}{T} - \alpha \frac{\rho_0}{\rho} \right) (\nabla T)^2 \\ & + \frac{2YN\Omega D_0 \xi}{3(1-\nu)k_B T} \exp\left(-\frac{E_a}{k_B T}\right) \frac{j^2 \rho^2 e^2}{3k_B^2 T} \end{aligned} \quad (3.9)$$

The meanings of the symbols used in Eq. (3.7) to (3.9) (those are not defined earlier) are given below.

$\alpha \approx$ temperature co-efficient of resistivity (TCR), $\rho_0 \approx$ reference resistivity, $Q^* \approx$ co-efficient of heat transfer, $\xi \approx$ co-efficient of thermal expansion.

It is to be noted here that in the above mathematical formulations (i.e. Eq. 3.7 to 3.9), the product $Z^* \rho$ is taken to be a constant according to ref. [61] for a given test environment. Here, Z^* is the effective charge number and ρ is the resistivity of Cu. However, from the AFD equations given by Eqs. (3.7) to (3.9), one can see that a small change in ρ will change the total AFD significantly as it will affect the Joule heating. Hence, the dependence of ρ on the temperature and stress fields in the metal is considered in the modeling while keeping $Z^* \rho$ constant.

In order to obtain the AFDs expressed by Eq. (3.7) to (3.9), first we need to obtain the distribution of current density (j), temperature (T) and stress (σ). Once these distributions are obtained for a given interconnect system and test condition, distributions of AFDs can be derived through Eq. (3.7) to (3.9). To obtain these distributions finite element method is used. The MultiphysicsTM finite element

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analysis software ANSYS® is used in this thesis work. Since the fields j , T , σ affects one another, coupled field analyses are required.

ANSYS® provides simultaneous coupling of the fields j , T , σ through the element ‘SOLID5’ [62]. However, the element ‘SOLID5’ ignores Joule heating [62] and hence this element cannot be used for the present study. On the other hand, elements ‘SOLID69’ and ‘SOLID45’ provide coupling between the fields j , T and T , σ respectively [62]. Thus a two-stage coupled field analyses are required in the present study.

In the first stage of analysis, the bottom surface of the substrate is kept at constant EM test temperature (T), which is the EM test temperature and a constant line current density (j) is applied as the boundary conditions. In this way the solution of coupled field analysis between the fields j , T is obtained. Also, from this solution, the nodal temperatures are retrieved for use in the second stage of simulation.

In the second stage of simulation, structural analysis is performed with the following three boundary conditions: (a) nodal temperatures obtained in the first stage of analysis are used as the boundary condition for nodal temperature; (b) the substrate bottom surface is kept fixed i.e. no displacement is allowed for the bottom surface of the Si substrate; and (c) the vertical symmetric plane is constrained to remain vertical arising from the mirror symmetrical nature of the structure under consideration. The above description is summarized in Figure 3.1. Since, built-in subroutines are available in ANSYS®, the coding of the complex mathematical formulation for the

FIG. 3.1: Methodology of two-stage simulation for CDFM.

FIG. 3.2: Typical meshing for line EM.

above analyses is not required for the present study (these formulations can be found in ref. [62]).

The basic structure after discretization for FEA is shown in Figure 3.2 and in Figure 3.3 for line and line-via EM respectively. The length, width and thickness of the structure are taken along the X, Y and Z (vertical direction) axes respectively. For example, the location of global origin of the coordinate system is shown in Figure 3.3,

and all the computational results are calculated with respect to this origin for line-via EM. To add realism, the full substrate thickness of 300 μm is considered in the model.

FIG. 3.3: Typical parts of via EM test structure after discretization. Dimensions in μm : SiN cap layer thickness: 0.05, Cylindrical via height between upper and lower level metallization: 0.68, Via diameter: 0.26, Line width including barrier layer: 0.4, Line thickness including barrier layer: 0.35, Barrier layer thickness (Ta): 0.025.

As the element aspect ratio is limited to 20 in the software, it is difficult to mesh all the sub-domains in the structure by using the “Mesh Tool” or “Map Mesh” to mesh the entire structure. Therefore, direct generation technique is used for discretization [62].

In addition, in case of line-via EM, complexity arises due to the fact that the circular via-end surfaces are connected to the rectangular metallization surfaces. Such connection requires both the cylindrical and rectangular co-ordinate systems to be considered in the model, and proper connection between the two co-ordinate systems is necessary. Hence, in this work, every node in the meshing is created by defining its co-ordinates and ‘brick’ element is formed to connect the adjacent 8 nodes with

defined material properties. A typical ‘brick’ element and mesh in certain portion of the cylindrical via are shown in Figure 3.4. With this way of building the finite

FIG. 3.4: (a) Typical ‘brick’ element, (b) meshing of the cylindrical via using ‘brick’ element.

element model, though it is tedious, the user can have full control and flexibility on the model. The thermo-mechanical material properties are listed in Table 3.1. The modeling parameters are tabulated in Table 3.2. Unit of number/(m³-sec) is used for AFD in this thesis.

As the thermo-mechanical stress gradient in the structure is considered as one of the driving forces, the SFT of the structure need to be considered in the model. For copper DD structure, SFT is in the range of 350 to 400°C [39-40], and 360°C SFT is taken for the present work (since, final annealing temperature is 360°C for our samples), unless otherwise stated.

The site of the maximum of positive total AFD is taken as void nucleation site in this work. The theoretical and experimental validation of this fact can be found in the ref. [26,60,63].

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Table 3.1: Thermo-mechanical material properties [63].

Material	Young's Modulus (GPa)	Poisson Ratio	Thermal Conductivity (W/m-K)	Co-efficient of Thermal Expansion (/°K)
Cu	129.8	0.339	379	16.5×10^{-6}
Ta	186.2	0.35	53.65	6.48×10^{-6}
SiN	265	0.27	0.8	1.5×10^{-6}
SiO ₂	71.4	0.16	1.75	0.68×10^{-6}
Si	130	0.28	61.9	4.4×10^{-6}

Table 3.2: Parameters used in finite element model.

Parameter	Material	Value	Reference
Electronic charge (e)	-	1.6021×10^{-19} Coulomb	-
Boltzmann's constant (k_B)	-	1.3867×10^{-23} Joule/°K	-
Atom concentration	Cu	8.44×10^{28} /m ³	-
Activation energy (E_a)	Cu	1.2 eV	From expt.
Effective charge number (Z^*)	Cu	4	[63]
Diffusion constant (D_0)	Cu	7.8×10^{-5} m ² /s	[63]
Atomic volume (Ω)	Cu	1.18×10^{-29} m ³	-
Resistivity @ 20 °C (ρ_0)	Cu	$(1.83 \text{ to } 2.02) \times 10^{-8}$ Ω-m	From expt.
Temperature coefficient of resistivity (α)	Cu	2.8×10^{-3} /°C	From expt.
Resistivity @ 300 °C (ρ)	Ta	70×10^{-8} Ω-m	[63]

3.4 Implementation of CDFM for Cu damascene interconnects

3.4.1 CDFM for line EM

Copper damascene interconnects of line-width 100 and 150 nm and with different aspect ratio (AR) are considered for the present investigation. Typical accelerated EM test conditions: $j=3.7 \text{ MA/cm}^2$ and $T=300^\circ\text{C}$ are imposed for line EM study in CDFM. Typical meshing for the CDFM is shown in Figure 3.2. The AFD distributions for interconnects of line-widths of 100 and 150 nm are shown in Figures 3.5 and 3.6 respectively. Uniform distributions of the AFD from temperature gradient induced driving force (with values of 4.9×10^{23} and 4.6×10^{23} number/ $\text{m}^3\text{-sec}$ for 100 nm and 150 nm wide lines respectively) are obtained for the present case. Hence, these distributions are not shown in Figures 3.5 and 3.6, though included in the computation of total AFD.

For comparison of EM in narrow and wide lines, CDFM is implemented for a wide ($0.7 \mu\text{m}$) Cu damascene line. Here activation energy, $E_a = 1 \text{ eV}$ is assumed [57]. The AFD distributions for this case are shown in Figure 3.7 and the maximum AFD is found to occur at the Cu/Cap interface. Experimentally, this interface is often found as failure site in Cu DD structure [57].

3.4.2 CDFM for line-via EM

CDFM is also implemented for Cu DD line-via EM test structures. The dimensions of various layers in the model are listed in Table 3.3. The two structures of line width $0.4 \mu\text{m}$ and $0.7 \mu\text{m}$ are considered and will be termed as narrow line-via

FIG. 3.5: AFD distributions in a small segment of 100 nm wide Cu interconnect. (a) AFD from EWF, (b) AFD from stress gradient induced driving force, (c) Total AFD.

and wide line-via structure respectively. The test structure under consideration along with the area of interest for line-via EM is shown in Figure 3.8. The test structure shown in Figure 3.8(a) and Figure 3.8(b) are called as M1 and M2 test structure respectively. Note that the cylindrical via is an integral part of the test line in case of M2 test structure. Figure 3.8(c) is showing various possible failure sites.

FIG. 3.6: AFD distributions in a small segment of 150 nm wide Cu interconnect. (a) AFD from EWF, (b) AFD from stress gradient induced driving force, (c) Total AFD.

The finite element model parameters are taken from the Table 3.2 except activation energy, TCR and room temperature resistivity. These parameters are taken as 0.6 eV, $3 \times 10^{-3} / ^\circ\text{C}$ and $1.7 \times 10^{-8} \Omega\text{-m}$ as found in line-via EM experiment.

Test current density of 0.8 MA/cm^2 and test temperature of 300°C are applied as EM stress conditions for line-via EM unless otherwise stated. The corresponding AFD distributions in the case of M1 test for narrow line-via and wide-line via are

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shown in Figure 3.9 and 3.10 respectively. The same in case of M2 test are shown in Figure 3.11 and 3.12 respectively.

FIG. 3.7: AFD distributions in a small segment of 0.7 μm wide Cu DD interconnect at typical EM test condition. (a) AFD from EWF, (b) AFD from stress gradient induced driving force, (c) AFD from temperature gradient induced driving force, (d) Total AFD.

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Table 3.3: Structural description.

Feature	Dimension in μm
Line width (including barrier layer)	0.4 and 0.7
Line thickness (including barrier layer)	0.35
Via diameter (including barrier layer)	0.26
Via height (distance between M1 and M2)	0.68
Barrier layer thickness	0.025
Cap layer thickness	0.05
Reservoir length (over hung)	0.04
Thickness of dielectric on cap layer of M2	0.5
Thickness of dielectric on substrate	0.5
Silicon substrate thickness	300

FIG. 3.8: Cu DD line-via EM test structure. (a) M1 test structure, (b) M2 test structure, (c) Possible failure sites.

FIG. 3.9: AFD distributions for narrow line-via in M1 test. (a) AFD from EWF, (b) AFD from stress gradient induced driving force, (c) AFD from temperature gradient induced driving force and (d) Total AFD.

FIG. 3.10: AFD distributions for wide line-via in M1 test. (a) AFD from EWF, (b) AFD from stress gradient induced driving force, (c) AFD from temperature gradient induced driving force and (d) Total AFD.

FIG. 3.11: AFD distributions for narrow line-via in M2 test. (a) AFD from EWF, (b) AFD from stress gradient induced driving force, (c) temperature gradient induced driving force and (d) Total AFD.

FIG. 3.12: AFD distributions for wide line-via in M2 test. (a) AFD from EWF, (b) AFD from stress gradient induced driving force, (c) AFD from temperature gradient induced driving force and (d) Total AFD.

3.5 Results and discussion on line EM

The AFD distributions shown in Figure 3.5 and 3.6 for 100 nm and 150 nm wide lines respectively indicate that EM failure must occur through the Cu/Ta interface as maximum AFD occurs near Cu/Ta interface for both the line widths. And the corresponding failure mechanism is expected to be different from the commonly observed Cu/cap interface failure mechanism.

Before EM testing, interconnect electrical resistances are measured at 26°C using EM tester. The interconnect resistivity is then computed from the sample resistance data and its cross sectional area measured by high resolution Transmission Electron Microscope (TEM). The resistivities for 100 nm and 150 nm wide lines are found to be 2.49 $\mu\Omega\text{-cm}$ and 2.35 $\mu\Omega\text{-cm}$ respectively. The average TCR in the temperature range from 26 to 325°C is found to be less than $3\times 10^{-3}/^{\circ}\text{C}$ as measured from a large sample size of more than 40, indicating no effect of the cross sectional size on the TCR of the interconnect line. Within the same line width regime, the electrical parameters obtained for our samples are found to be better than the reported data thus far [64-65]. From our electrical measurement, these interconnects are fulfilling the requirement for future generation technology in intermediate wiring according to the ‘International Technology Roadmap for Semiconductors’ [66].

The electrical parameters such as resistivity and TCR which are obtained for these interconnect have been used in simulation (see Table 3.2). Plots for TCR data of six samples are shown in Figure 3.13.

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Package level EM experiments are carried out for 100 nm and 150 nm wide copper interconnects. The samples were fabricated by damascene technology. To improve the lithographic resolution in patterning the trench, a specially designed alternating-phase-shift-mask with alternating phase shifted scatter bars is used. These samples are fabricated at Institute of Microelectronics, Singapore. A note on sample preparation is described in Appendix I. The EM test module system (Qualitau, MIRA) and a typical packaged sample are shown in Figure 3.14. The experimental line EM test condition of the above mentioned samples is summarized in Table 3.4.

FIG. 3.13: Resistance Vs temperature plots for few 100 nm wide Cu lines.

FIG. 3.14: (a) Test module (Qualitau, MIRA). (b) A typical packaged sample.

Table 3.4: Line EM test condition.

Line width (nm)	Test temperature (°C)	Test current density (MA/cm ²)	Simulation performed
150	275	3.7	No
150	300	3.7	Yes
150	325	3.7	No
100	300	3.7	Yes
100	300	1.5	No

Extensive physical failure analysis is performed on the stressed samples using Focused Ion Beam-Scanning Electron Microscope (FIB-SEM) tool and TEM. Figure 3.15 shows the images of the failed 100 nm wide interconnect (AR=5) where the failure is found to have occurred at the bottom Cu/Ta interface while the top Cu/cap layer interface remains unaffected. This is in contrast to the EM failure observed for Cu line width ranging from 0.28 to 0.7 μm [66-68]. Many small voids are observed at the Cu/Ta interface rather than a catastrophic void in the failed line. It is also observed that the void density at Cu/Ta interface decreases rapidly with the increase in distance from the cathode end. Thus majority of the voids occur near the cathode end. This failure characteristic observed in the 100 nm wide lines is found to be the same for both test current densities.

The images of the failed 150 nm wide interconnects are shown in Figure 3.16. In this case, cathode depletion type failure is observed. Apart from cathode depletion, a few small voids are also observed at the bottom Cu/Ta interface as in the case of the 100 nm wide interconnect. For the failed 150 nm line width samples, the line shape near the cathode is observed as shown in Figure 3.16(a) where the bottom portion of

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FIG. 3.15: Failed sample images of 100 nm wide lines. (a) Near the cathode, $T=325^{\circ}\text{C}$, (b) 20 μm away from cathode, $T=300^{\circ}\text{C}$.

FIG. 3.16: FIB X-sections of failed samples of 150 nm wide lines near cathode. (a) $T=325^{\circ}\text{C}$, (b) $T=300^{\circ}\text{C}$.

the line is more depleted as compared to the top portion of the line, and from this observation, it seems that the cathode thinning occurred from the bottom Cu/Ta

interface at the beginning of the EM mass transport. This failure characteristic is found to be independent of test temperatures used in this work.

Since the Cu/cap interface remains unaffected by EM, one may speculate that there may be formation of a copper silicide layer near Cu/cap layer [69]. However, energy dispersive X-ray (EDX) analysis near Cu/cap layer and high resolution TEM images on failed samples do not show any evidence of such silicide formation. Figure 3.17 shows some TEM x-section images of failed samples with EDX analysis (the uncertainty limit in the concentration measurement data presented in Figure 3.17(a) is 2%).

FIG. 3.17: TEM images of failed samples near Cu/cap interface. Silicide layer at Cu/cap interface is not observed.

The Arrhenius relation (for 150 nm wide lines) is shown in Figure 3.18 and activation energy is found to be 1.2 eV which is higher than the commonly observed

activation energy (0.8 to 1 eV [67-68]) and indeed represents a different failure mechanism as predicted by CDFM.

FIG. 3.18: Arrhenius relationship for line EM.

3.6 Results and discussion on line-via EM

If EWF acts the sole driving force for EM, the void locations will be near/at the zone of high current density for the via-line structure as shown in Figure 3.8(c). Therefore sites D and B (see Figure 3.8(c)) will be the expected failure sites in M1 and M2 tests respectively. Here, M1 test refers to the EM test of the lower level metallization (see Figure 3.8(a)) and M2 test refers to the EM test of the upper level metallization (see Figure 3.8(b)) in a two-level Cu DD test structure.

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Upon careful compilation of experimental work reported in literatures, it can be found that the void locations observed in the Cu DD structures are indeed at site D in the M1 test. However, the failure sites in M2 tests are at sites A, B, and C with sites A and C more frequently observed [67,70-75]. Similar discrepancies on the failure sites are also observed for Al-based interconnects [76-82]. Therefore, the experimental results suggest that EWF might not be the only driving force in the EM failure process.

The contribution of three sources of driving force to the total AFD is listed in Table 3.5 and these AFD contribution values is found to be within the range of reported values [60,83,84]. The results listed in Table 3.5 are obtained from the CDFM as described earlier.

Table 3.5: Contribution to the total AFD from different sources in submicron Cu DD line-via EM.

Stress condition T=300 ° C, j=0.8 MA/cm ²	Test type: M1-test		Stress condition T=300 ° C, j=0.8 MA/cm ²	Test type: M2-test	
	Line width (μm)			Line width (μm)	
	0.4	0.7		0.4	0.7
EWf	9.2%	21.8%	EWf	8.1%	16.5%
Stress gradient induced driving force	79.9%	68.3%	Stress gradient induced driving force	79.4%	65.5%
Temperature gradient induced driving force	10.9%	9.9%	Temperature gradient induced driving force	12.5%	18.0%
Total AFD	100%	100%	Total AFD	100%	100%

In the line-via EM case, the AFDs from the EWF, stress gradient induced driving force and temperature gradient induced driving force are found to be of same

order. The maximum values of temperature and stress gradients are found to be typically $0.9 \text{ K}/\mu\text{m}$ and $5 \times 10^3 \text{ GPa}/\mu\text{m}$ at typical accelerated test condition.

Notice the magnitudes of temperature and stress gradients obtained. The temperature gradient obtained here is of the same order as taken in Eq. (3.5) for comparison purpose. It is therefore expected that temperature gradient induced driving force will take part in EM failure process, since temperature gradient with lower than this values are reported to effect the failure time significantly [52]. The magnitude of stress gradient obtained here is at least 5 orders of higher than that of taken in Eq. (3.3) for comparison purpose. Thus it is expected that AFD from stress gradient induced driving force will be the dominant factor in the EM failure process. Experimental validation of this fact is presented in later chapters of this thesis.

We will now present results and discussion on M1 test and M2 test separately in the following two sections.

3.6.1 In case of M1 test

The site of maximum total AFD is found to be in the M1 line underneath the cylindrical via and at the external corner of M1 line for the narrow line-via structure (Figure 3.9(d)). For the case of wide line structure, the site of maximum total AFD is found to be in the M1 line underneath the cylindrical via (Figure 3.10(d)).

It is also found that the occurrence of maximum of the total AFD at site E (Figure 3.8(c)) is a strong function of SFT and EM test condition. At higher EM test temperature (higher than 300°C) or at higher current density (higher than 0.8 MA/cm²), site E will no longer be the void nucleation site. On the other hand, the occurrence of the site of maximum of total AFD at the site D (Figure 3.8(c)) is independent of the accelerated test conditions and line widths, and hence this site (i.e. site D) can be considered as an intrinsic weak site of the structure under consideration. This possibly explains the fact that site E failure is less often observed experimentally as compared to site D.

AFD computation at lower test temperature reveals that the population of failure through site E increases for the case of the narrow line-via structure [84]. The distribution of the total AFD for narrow and wide line-via structures are shown in Figure 3.19 for the EM test conditions: T=250°C and j=0.8 MA/cm². It can be seen from this figure that the site of the maximum of total AFD occurs at the site E for the narrow line-via structure while the failure site remains at site D for the wide line-via structure. It is therefore expected that if the line width is continuously decreasing, the population of the site E failure will increase with a lower current density EM stressing. In fact, it could represent an important failure site under normal operating condition for the very narrow line width structures at 65 nm technology node and below [84].

The reason of the increase in the site E failure population is due to the increases in the contribution of the stress gradient induced driving force and the decreases in the contribution of the EWF as can be seen from Table 3.5. From this table, one can see that as the line width decreases, the AFD from stress gradient

FIG. 3.19: Total AFD distributions for a low temperature EM test.

induced driving force to the total AFD increases. This is because as the line width decreases, the degree of non-uniformity in the current density and temperature fields also decrease, resulting in a decrease in the flux divergence contribution from the EWF and temperature gradient induced driving force. This can be seen in Figures 3.9 and 3.10.

The reason for the increase in the non-uniformity in the current density and temperature fields is due to the higher value of the total current in the case of wide line-via and that the total current has to flow through the cylindrical via of the same dimension as in the narrow line-via case. Also, with the increase in line width and thus the increase in the total current, total heat generation in the structure increases. This increases the metallization temperature, which in turn reduces the temperature difference between the metallization temperature and the SFT. Hence, the thermo-mechanical stress is reduced, rendering a reduction in the contribution from stress gradient induced driving force to the total AFD.

As the line width changes, the relative percentage change of the contributions to total AFD due to the various driving forces can be calculated from Table 3.5. For M1 test, the relative percentage change of AFD from EWF is $\frac{|21.8-9.2|}{21.8} \times 100 = 57.8\%$ and is the highest among the three [60,84]. This result implies that the EWF is the most responsible factor that account for the difference in the EM performance of the two structures with different line widths. As the line width decreases, the role of the EWF on total AFD decreases.

3.6.2 In case of M2 test

In this case, the site of maximum of the total AFD occurs within the cylindrical via near the bottom of the via for structures of both line widths (see Figures 3.11 and 3.12).

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For the M2 test structure, there exist two current crowding zones, namely at the site B and site C, and that the site B is the much crowded zone than the site C (see Figure 3.8(c)). However, experimentally it is found that failure often occurs at the site C. This is because maximum of the AFD occurs at the site C and which is an inherent weak site in the M2 test, just like site D in the M1 test as discussed earlier.

When the difference between the metallization temperature during EM test and SFT is as small as 5 °C, it is found that stress gradient induced driving force contribution will decrease, and hence site B failure will become more likely to occur. Thus site B failure is anticipated at certain EM stress condition. An experimental verification of this fact will be interesting.

In some M2 test, failure at site A is also observed although this site is not a site of maximum positive AFD. This failure is likely to be due to the enhanced surface/interface diffusion and can be explained from the stress concentration in the test structure. The hydrostatic stress distribution in the structure is computed at the EM test condition (used in the present work), and it is shown in Figure 3.20 for the narrow and wide line-via M2 test structures. Maximum stress concentration occurs at the site A for both structures under consideration in the M2 test. Importantly note that, the magnitude of stress concentration is within the reported value of the critical stress (about 50 to 100 MPa) for void nucleation in Cu metallization [85]. Thus the site A failure could be due the stress concentration, that arises from thermo-mechanical mismatch [84].

The distributions of the normal stress and the stress along the metal length in the SiN cap layer are also computed and shown in Figures 3.21 and 3.22 for narrow and wide line-via structures respectively.

From these figures, one can see that the stress gradients are high in the cap layer at the site A. The stress state changes from tensile to compressive within a short distance. This is expected as the thickness of the cap layer is very small as compared to that of the Cu under-layer, and because of the large thermal mismatch between Cu and the cap layer, the cap layer is forced by the Cu layer to contract, and hence the existence of compressive stress in the cap layer adjacent to the Cu metallization. However, at the top of the cap layer adjacent to undoped-silica-glass, the stress in the cap layer is tensile. Thus a very large stress gradient occurs in the cap layer at the failure site A.

FIG. 3.20: Hydrostatic stress distributions (in MPa) at EM test condition. (a) Narrow line-via, (b) Wide line-via.

FIG. 3.21: Stress distributions of stresses at the bottom of the SiN cap layer for narrow line structure. (a) Normal stress and (b) Stress along the length. As the underlayer is no longer Cu on the left side of the cap layer, the stress is tensile in nature while, when Cu underlayer exists, the stress is compressive in nature, resulting very high stress gradient at site A in the structure. Here, MPa unit is used for stress.

Due to the high stress gradient in the cap layer at the site A, the possibility of cracking/delaminating of the cap layer cannot be ignored especially at the edges/corner of the structure [84]. The detail explanation of the possibility of cracking/delaminating of SiN cap layer sandwiched between metal and dielectric layers can be found in ref. [86-88]. The cracking of the cap layer will leave the Cu top layer unprotected at that site, and surface/interface diffusion of Cu atoms will thus be enhanced. From the calculation, one can see that if the thickness of the cap layer is

FIG. 3.22: Similar stress distributions as in FIG. 3.21, but it is for wide line-via structure.

increased, one could improve the confinement capability of cap layer, thus preventing site A failure [84].

The stress distribution in the cap layer and the AFD distribution in the Cu film clearly indicates two favorable sites for void location in the case of M2 test, namely the site A and site C, and bimodality in the EM failure is therefore expected which have been seen experimentally [73,89]. In fact, the co-existence of the site A and site C failures were confirmed by the work done by *Lee et al.* [89], where there were 25% of site A and 75% of site C failure in their EM tests.

With the increase in the line width, the magnitude of the stress reduces (see Figure 3.20(a) and Figure 3.20(b)). Therefore, the proportion of site A failure is expected to increase with the decrease in the line width. Since site C is an inherent weak site in M2 test, bimodal failure (contains failure at site A and failure at site C) will be more obvious for narrower lines.

From the above discussion, a question may arise as to why the similar stress state as obtained at the site A is not found at the site E? This can be explained by the fact that the top surface of M2 metallization is covered by the non metallic cap layer while the bottom surface of M1 metallization is covered by the metallic barrier layer. Therefore, asymmetry on stress state is expected due to the difference in the material properties of these two materials as compared to Cu material properties.

The computation of the percentage change of the contribution to total AFD due to the three driving forces as the line width changes (from Table 3.5) suggests that the EWF is also the most responsible factor that attribute to the difference in EM performances of the structure with different line width for M2 test. The decreasing role of the EWF on total AFD with decreasing line width is also observed in M2 test, similar to the case of M1 test [84].

3.7 Summary

Atomic fluxes that arise from stress gradient induced driving force, temperature gradient induced driving force and surface tension induced driving force are compared with that from EWF and it is found that stress gradient induced driving force and

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temperature gradient induced driving force are important as they can give rise atomic flux of the same order as that due to EWF.

Finite element model combining EWF, stress gradient induced driving force and temperature gradient induced driving force is developed for line and line-via EM. In both line and line-via EM cases, stress gradient induced driving force is found to dominate at the beginning of EM test and this driving force cannot be suppressed totally due to complex temperature processing history during samples preparation.

The line EM model predicts that for the line widths of 100 nm and 150 nm, the Cu/Ta bottom interface (instead of Cu/cap) should be vulnerable to EM and the failure mechanism should be different from the commonly observed failure mechanism in Cu DD interconnects. These facts are verified experimentally and it is indeed observed that Cu/Ta interface is weak site with EM mass transport activation energy of 1.2 eV.

A detail investigation on the nature of void location in line-via EM is investigated. The total AFD distributions are shown for submicron Cu dual damascene line-via structure. The asymmetric nature of failure characteristics in case of Cu DD line-via structure is presented.

The model accurately predicts the void locations in both the M1 and M2 tests as observed experimentally. It is shown here that few sites are inherently weak in a line-via structure which are the most commonly observed void locations, and few of them are conditional. The possibility of bimodality is also described.

Chapter 4

IMPACT OF STRESS FREE TEMPERATURE ON ELECTROMIGRATION CHARACTERISTICS

4.1 Introduction

In the third chapter; stress and corresponding stress gradient induced driving force are identified as dominant source of AFD at the beginning of the EM test. Since the magnitude of stress and stress gradient depends on the sample SFT and EM test temperature, it would be possible to improve the EM life-time by reducing the SFT which in turn reduces the metallization stress and/or stress gradients as stress (σ) in the interconnect is related by

$$\sigma \propto (SFT - T_m) \quad (4.1)$$

where, T_m is the metallization temperature (including Joule heating) at EM test condition.

From Eq. (4.1), one can see the metallization stress state is dependent on the difference in SFT and metallization temperature at EM test condition. Thus one would

expect different EM characteristics by varying difference in the SFT and EM test condition [90].

It is the purpose of this chapter to study the impact of the SFT on the EM characteristics for Cu DD submicron line-via interconnects. The impact of the SFT on the EM is studied by varying the SFT in CDFM followed by EM experiments.

4.2 Relation between failure time and AFD

There are different ways to show that the interconnect failure time (t_f) is inversely proportional to AFD [50,26]. A similar relation between t_f and AFD can also be established by following manner.

Lets ΔN be the number of ions (or atoms) accumulated in a small length of Δl of the metallization in time period Δt due to the presence of flux divergence of value $\nabla \cdot J$, then for infinitesimal time period, one can have

$$\Delta N = \lim_{\Delta t \rightarrow 0} \delta h \Delta l \Delta t (\nabla \cdot J) \quad (4.2)$$

where δ and h are the effective diffusion path width and film thickness (or diffusion path thickness) respectively. This description on the AFD is schematically shown in Figure 4.1. Multiplying Eq. (4.2) by atomic volume (Ω), the growth rate of the volume V of mass depletion or accumulation can be written as [91]

$J_{in}(t)$ = Incoming atomic flux at time t

$J_{out}(t+\Delta t)$ = Outgoing atomic flux at time $t+\Delta t$

$$\nabla J = \frac{J_{out} - J_{in}}{\Delta l}$$

FIG. 4.1: A schematic representation of AFD for infinitesimal time period.

$$\frac{\partial V}{\partial t} = \delta h \Delta l \Omega (\nabla \cdot J) \quad (4.3)$$

Integrating Eq. (4.3) yields,

$$\int_0^{V_c} \partial V = \Omega \Delta l \int_0^{t_f} \delta h (\nabla \cdot J) \partial t \quad (4.4)$$

where, V_c is the critical volume of mass depletion or accumulation required for failure to occur.

The variation of AFD with time is complex as there are many interacting fields that produce resultant AFD, and they do not remain constant over a given period of time (once the mass depletion or accumulation begin) because of the increasing inhomogeneity of the interconnect. The term $\nabla \cdot J$ is a function of time and cannot be taken outside the integration. Likewise for δ and h , which are also vary during the

failure process. In order to obtain a qualitative relationship between the time to failure and AFD; we may consider the average values of AFD ($\overline{\nabla \cdot J}$), effective width of the diffusion path ($\bar{\delta}$) and thickness ($\bar{h}$) over the time period t_f . Thus the Eq. (4.4) is reduced to [92]

$$t_f = \frac{V_c}{\Omega \Delta l \bar{\delta} \bar{h} \overline{\nabla \cdot J}} \quad (4.5)$$

And hence qualitatively,

$$t_f \propto \frac{1}{AFD} \quad (4.6)$$

Thus it is anticipated that by reducing the AFD, interconnect life-time can be improved. On the other hand, reduction in AFD can be obtained by reducing interconnect SFT [90].

4.3 Case studies by CDFM on the impact of SFT in EM

In order to investigate the impact of the SFT on the EM, CDFM is studied for three cases of Cu line-via structure, which is summarized in Table 4.1.

Since, analysis of temperature-stress coupling is performed in the second stage of the CDFM (see chapter 3), it is necessary to consider the SFT in the second stage of the simulation. The default value of the SFT for stress related simulation in ANSYS® is zero units. The input for the SFT in the software can be given by various

Table 4.1: Different cases considered for the study of the impact of SFT on EM.

Cases	Test type	Structure type	EM test condition	SFT range	Experiment performed
Case 1	M1	Narrow line-via (see Table 3.3)	$T=300^{\circ}\text{C}$ and $j=0.8\text{ MA/cm}^2$	360 to 200°C	No
Case 2	M2	Narrow line-via (see Table 3.3)	$T=300^{\circ}\text{C}$ and $j=0.8\text{ MA/cm}^2$	360 to 200°C	No
Case 3	M1	Wide line-via (see Table 3.3)	$T=300^{\circ}\text{C}$ and $j=1\text{ MA/cm}^2$	360 to 340°C	Yes

ways [62]. In our study, the SFT was given as a materials reference temperature in the list of material property. This input was varied with desired values to study the effect of the SFT by CDFM.

4.4 Experimental study on the impact of SFT in EM

Cu line-via EM test structure (see Figure 3.8(a)) is fabricated for the present study using $0.18\text{ }\mu\text{m}$ Cu/oxide dual damascene technology. As a final process step, annealing at temperature 360°C for 30 minutes is performed for all the wafers. These samples are fabricated at Institute of Microelectronics, Singapore. A note on the samples preparation is given in Appendix II.

Three sets of package level EM test have been conducted at 300°C with a current density of 1 MA/cm^2 . In order to reduce the SFT, additional thermal annealing (in normal laboratory ambient) at temperatures of 100 and 200°C for 48 hrs is performed prior to EM tests for two set of samples. Such additional thermal annealing is not performed for third set of samples.

Since the void nucleation and growth before a sharp increase in the resistance account for the major portion of the EM failure time, and during this period, the stress and temperature gradient induced atomic migration dominate [83], the failure criterion for the resistance change is set at only 2% in order to observe the effect of the SFT in this study. The cumulative density function (CDF) of the EM failures is shown in Figure 4.2. The median-time-to-failure (t_{50}) for the three EM tests is listed in Table 4.2.

The resistance change profiles of the three EM tests are shown in Figure 4.3. For all the three cases, step like resistance change is found.

Physical failure analysis is performed using FIB-SEM tool on stressed samples and their micrographs are shown in Figure 4.4. In all the three cases, failure occurs in the M1 line underneath the cylindrical via.

4.5 Results and discussion

Before we discuss the effect of the SFT on the EM, it is necessary to recall the different failure sites as shown in Figure 3.8(c). The effect of SFT variation for the Case 1 (as described in Table 4.1) is summarized in Table 4.3. It can be seen from this table that site E failure will occur when the SFT is higher than 360°C, and its failure mechanism is dominated by the stress gradient induced driving force. The effects of the decrease in test temperature and SFT are opposite. It is noticed that the value of the total AFD decreases with the decrease in SFT, hence a lower SFT is preferred for improving the interconnect life-time, as described earlier.

FIG. 4.2: EM failure distributions.

Table 4.2: Accelerated EM test data.

Test no.	t_{50} (hrs)	Additional annealing	Remarks
1	1136.56	100 °C @ 48 hrs	Best EM performance is obtained for the 2 nd test.
2	142.89	200 °C @ 48 hrs	
3	113.67	Not performed

FIG. 4.3: Resistance change profiles during EM mass transport. Here, R is the instantaneous resistance and R_0 is the initial resistance.

FIG. 4.4: SEM images of failed samples. Images (a), (b), (c) correspond to cases of anneal at 100°C, 200°C and without additional anneal respectively.

Table 4.3: Effect of different SFT for the Case 1.

SFT (°C)	Failure site	Dominant factor
360	site-D and site-E	EWf and Stress gradient induced driving force
340	site-D	EWf
300	site-D	EWf
250	site-D (not on the M1 surface but inside the M1 below the cylindrical via [*])	EWf
200	site-D (* as above)	EWf

The total AFD distribution for the Case 2 (see Table 4.1) is shown in Figure 4.5 for two different SFT. From this figure, it can be seen that as the SFT decreases, the volume of the positive AFD zone increases and it covers the entire cylindrical via, implying that the void can be anywhere in the via (i.e. site A, site B and site C). This AFD zone is found to increase and cover the M2 line on further decrease in the SFT. Also, the stress value of the failure site A decreases with the decrease in the SFT, and the stress state at this failure site changes from tensile to compressive at about 323 °C as shown in Figure 4.6 [90]. Thus failure site A is not expected for sample with SFT below 323 °C when tested with the used test condition.

From the above investigations (Case 1 and Case 2), it is understood that by reducing the SFT, the AFD can be reduced. Note that, it would be easier to verify above facts by considering M1 test instead of M2 test. This is because in M2 test, multimodal failure may occur (as discussed in chapter 3) and population of such failure may change with SFT and it would difficult to understand the effect of the SFT on the EM, and hence M1 test (like Case 1 and Case 3 in Table 4.1) should be chosen to verify the impact of the SFT on the EM experimentally.

FIG. 4.5: Total AFD distributions for two different SFT for the Case 2.

FIG. 4.6: Stress state of the failure site A as a function of SFT for the Case 2.

CDFM is also studied for three SFT of 360, 350 and 340°C for Cu damascene line-via structure (Case 3 in Table 4.1). The schematic of the structure is shown in previous chapter in Figure 3.8(a). The EM test temperature of 300°C and current

density of 1 MA/cm^2 are applied as boundary condition in CDFM. Line width of $0.7 \text{ }\mu\text{m}$ and thickness of $0.35 \text{ }\mu\text{m}$ is used in the model. The other dimensional parameters such as Ta barrier layer thickness etc. are taken as described in chapter 3. Other modeling parameters are also kept same as described in chapter 3. The total AFD distributions for three SFTs are shown in Figure 4.7.

In the following section further investigation for the Case 3 is presented in order to understand the relation between t_{50} and AFD from model and experiments.

FIG. 4.7: AFD distributions for three different SFT. (a) SFT=360°C, (b) SFT=350°C and (c) SFT=340°C.

In order to estimate the SFT of samples which undergone additional thermal annealing prior to EM experiment, experimental stress measurement data [93-94] are used (the mechanism of stress relaxation due to high thermal storage can also be found in ref. [93-94]). From the references [94-95], the stress in the Cu after annealing are 0.9 and 0.95 of the initial stress for annealing at 200 and 100°C respectively. Since stress is proportional to the difference between the SFT and the temperature of the Cu, one can therefore compute the SFT after annealing given the SFT of the original Cu line is 360°C. With this computation, the SFT for 100 and 200°C annealed samples are estimated to be 348 and 344°C respectively [92]. Thus the range of SFT in this study is 360 to 344°C.

From Table 4.2, it can be seen that the EM life-time improves due to the reduction in the SFT, which is obtained simply by an additional thermal annealing. This improvement is found to be about 25.7 and 20.1% for SFT of 344 and 348°C respectively with respect to that for SFT of 360°C.

For all the three cases, step like resistance change is found. The time for the step formation in the resistance change profile is found to be longest in case of the samples annealed at 200°C prior to EM test. It is also noticed that the step formation in the resistance change profile is delayed due to reduction in the SFT (see Figure. 4.3), and hence increasing the EM life-time.

It is to be noted here that failure site depends on the SFT as well as on the EM test condition [90,92]. Notice that the AFD distributions (see Figure 4.7) predict that for SFT in the range 360 to 340°C and when EM test condition are $T=300^{\circ}\text{C}$, $j=1$

MA/cm², the failure site should be in the M1 test line underneath the via bottom. From physical failure analysis (see Figure 4.4) the site underneath the via bottom in the M1 line is indeed observed as the failure site.

From the AFD distributions for different SFT (see Figure 4.7), one can notice that AFD decreases with decrease in the SFT. Thus reducing SFT, AFD that exists at

FIG. 4.8: Impact of the SFT on the EM performance.

the beginning of EM test in the metallization can be reduced [90,92]. Since the failure time is inversely proportional to AFD as described earlier, one expects a similar trend between t_{50} and $1/AFD$. The variation of normalized $1/AFD_{max}$ (normalized by $1/AFD_{max}$ for SFT=360°C) and the variation of normalized t_{50} (normalized by t_{50} for SFT=360°C) are studied. These variations are shown in Figure 4.8.

Although a similar trend is observed between the experimental and simulation results, deviation is also noticed especially toward the lower SFT (see Figure 4.8). This deviation may result from the estimation of the SFT for our samples from the data presented in ref. [93-94]. Also, deviation may occur due to the assumption that AFD (that occurs at the beginning of EM test) remains constant in the EM failure process.

4.6 Summary

The CDFM for different SFTs for submicron Cu damascene line-via structure shows decrease in AFD as SFT decreases. On the other hand, failure time is shown to be inversely proportional to AFD. Thus by decreasing the SFT, the EM life-time can be improved. Experiments are conducted and it is shown that EM life-time improved upon decreasing the SFT of the structure under consideration. The reduction of SFT can be obtained easily by performing additional thermal annealing. The CDFM also predicts the failure site should be in the test line under the cylindrical via which is indeed experimentally found as failure site.

Chapter 5

ELECTROMIGRATION DEGRADATION AND VOID EVOLUTION

5.1 Introduction

As discussed in chapter 4, the variation of AFDs with time during failure the process is complex due to the fact that fields like current density, temperature and stress are coupled in nature. Additionally, complication in structural stability of the interconnect during EM degradation arises due to the increasing inhomogeneity of the structure with time once the mass transport is started.

It is the purpose of this chapter to study the variation of the AFDs from the sources of three driving forces. The three driving forces considered here are again the EWF, stress gradient induced driving force and temperature gradient induced driving force and the CDFM is further extended to study dynamic EM characteristics. Cu DD line-via test structure is employed in this study. A schematic of the test structure is shown in Figure 3.8(a). EM experiment is also conducted. From the dynamic CDFM, resistance change profile and critical void volume required for failure to occur are

obtained and are compared with that obtained from experiment. The variation of AFDs with degradation time is also presented.

5.2 Model description

Traditionally EM models are based on solution of coupled diffusion equations. Recently in the driving force formalism of the EM, two approaches are in parallel progress using FEM [25-26,60,63,83, 95-98]. Most of these models combine at least three driving forces for EM. These three driving forces are EWF, stress gradient induced driving force and temperature gradient induced driving force. In the first approach, the diffusion time of metal atoms (or vacancies) in interconnect under EM test is indirectly coupled with the other interacting fields such as current, temperature, stress etc. [26,60,63,83,95]. In order to relate the physical time with the EM failure process, additional equations are used. These additional equations represent the amount of volume depleted or accumulated as a function of time. And in the second approach, the diffusion time is directly coupled with the other interacting fields [25,96-98]. Both of these approaches have their own advantages and disadvantages [25]. For example, from the first approach it is possible to separate the contribution of different driving forces and their AFDs which is not possible from the second approach, since the latter approach gives the AFD distribution from the resultant driving forces as function of time. In this work, dynamic CDFM is implemented for studying EM in Cu DD line-via structure using the first approach.

The site of the maximum total positive AFD is taken as the void nucleation site in this work, similar to work done in ref. [25-26,60,63,83,95,98]. It is also proven experimentally by Duan and Shen [99]. The value of the EM failure activation energy for the structure under consideration is taken to be 0.6 eV as found experimentally [63]. The list of material properties and other modeling parameters can be found in ref. [63].

First of all, the CDFM for Cu line-via interconnect as discussed in chapter 3 is implemented. Additionally, an array is produced to store the total AFD value of each element in ascending order at the end of every iteration. In order to simulate the void growth process, the variation of AFDs and change of void shape during the failure process, one needs to delete the element from the structure possessing highest AFD (irreversible property of EM allows us to delete elements to form the void in the model) and then repeat the whole simulation again until failure occurs as defined by the resistance increase to a pre-selected level. However, this process is time consuming.

Preliminary investigation is performed on the above procedure and it is found that deleting last 5 elements per iteration from the stored array will not change the resulting void shape and size as compared to that after 5 iterations of deleting one element per iteration for the mesh density used in this work. On the other hand, deleting more than 5 elements will not preserve the void size and shape. Thus the procedure of deleting 5 elements at a time is adapted here to speed up the simulation time by 5 times (the typical time to execute an iteration is 7 hrs). Thus in every

iteration, the last 5 elements stored in the array as defined earlier are deleted and the whole simulation is repeated until failure occurs. The model flow chart is shown in Figure 5.1.

FIG. 5.1: Model flow chart.

In order to relate the simulated degradation time with the physical time of the EM process, one can proceed as follows. Since AFD represents the number of atoms

decreasing per unit volume per unit time, the depletion time t_e for an element of volume v_e can be expressed as

$$t_e = \frac{S}{v_e \times AFD_e} \quad (5.1)$$

where AFD_e is the total AFD value of the depleting element and S is a (dimensionless) proportional constant.

Since 5 elements are deleted in an iteration, the corresponding physical time for an iteration can be given by

$$t_i = \sum_{e=1}^5 t_e \quad (5.2)$$

where, t_i is the depletion time in i th iteration. It is to be noted here that the sum in Eq. (5.2) is taken for the last 5 elements from the array which stores the element AFD values in ascending order.

At the end of every iteration, the voltage difference between the ends of the conductor is obtained and this voltage difference is divided by the applied current to obtain the resistance. The conductor resistance is then checked with the pre-selected failure criterion. The process continues until failure occurs. Once the failure occurs, the EM failure time is estimated as

$$t_f = \sum_{i=1}^m t_i \quad (5.3)$$

where m is the final iteration number at which failure occurs.

The void volume at failure will be two times the total volume of all the deleted elements. The multiplication factor of 2 arises since only one half of the structure is considered in the model.

5.3 Experimental

5.3.1 Sample fabrication

Cu DD line-via test structure is fabricated for the present study. A schematic of the structure is shown in Figure 3.8(a). These samples are fabricated at Institute of Microelectronics, Singapore. A note on the fabrication process is given in the appendix II. The line width of the structure used here is 0.7 μm . A 50 nm thick SiN layer is used as cap/etch-stop layer in the present EM test structure. The lines are 0.35 μm thick and the via diameter (connecting M1 and M2 lines) is 0.26 μm . As a final process step, all wafers are annealed at 360°C for 30 minutes (flow of gases: N₂ (90%) and H₂ (10%) in a pressure of 92 kPa are maintained during the final annealing process). Hence the SFT of the structure can be considered to be as 360°C.

5.3.2 EM test and physical failure analysis

FIG. 5.2: SEM image of a failed sample.

In order to obtain resistance change behavior and final void location, EM test is conducted. A package level EM test is conducted at 300°C with a current density of 1MA/cm² employing 6 samples. The failure criterion is set to 2% resistance change in this EM test. From previous experience on EM test on the same sample, we noticed that failure criterion with more than 2% resistance increase does not change the median-time-to-failure significantly in comparison to the case of the failure criterion of 2% resistance change. This is because the rate of change of resistance becomes very high after the 2% change in the resistance. On the other hand, the void size will be much larger in the case where failure criterion is set at more than 2% resistance change, which will lead a wrong estimation of the void size at the failure.

Physical failure analysis is performed using FIB-SEM. Figure 5.2 is showing micrograph of a failed sample. The failure is found to occur in the M1 metallization underneath the cylindrical via. The parameters r and d shown in Figure 5.2 are found to be 0.19 μm and 45 nm. Assuming the void is a cylindrical shaped void of diameter r with a height of d , the volume of the void is comes out to be $1.3 \times 10^{-21} \text{ m}^3$.

5.4 Results and discussion

5.4.1 Resistance change during EM failure process

The resistance change and void volume as a function of time are obtained from dynamic CDFM and are shown in Figure 5.3. In these evaluations the unit of time is an arbitrary unit, since the constant S (in Eq. 5.1) is unknown. An estimation of the value of this constant is obtained as follows.

FIG. 5.3: Void volume and resistance change profile as a function of time.

The initial resistance (R_0) of the samples employed in this study is found to be about 100 Ω experimentally at the EM test condition. On the other hand the initial resistance (R_v) of the small portion considered in the simulation (this small portion is shown as area of interest in Figure 3.8(a)) is found to be about 1.5 Ω from simulation. Since $R_0 \gg R_v(t=0)$, and assuming the resistance change occurs only due to failure in the via link shown Figure 5.2, then the resistance of the structure can be written as:

$$R(t) = R_0 + R_v(t) / 2 \quad (5.4)$$

The second term in the above equation is divided by 2 to take account the full width of structure, since only one half of the structure is considered in the model. The resistance change profile is then obtained from

$$\frac{R(t)}{R_0} \approx \frac{R_0 + R_v(t) / 2}{R_0 + R_v(t=0) / 2} \quad (5.5)$$

The value of R_v as a function of iteration number is obtained from model and Eq. (5.2)-(5.5) are evaluated for every iteration. The value of the fitting parameter S is estimated by fitting the simulated resistance change profile with that obtained from experiment. From the fitting with experimental data, the range of the value of S is found to be 1.7×10^{13} to 4.1×10^{13} . Figure 5.4 shows the resistance change profiles from experiment and model with S value of 2.95×10^{13} .

The void volume at failure (V_c) can be determined as described earlier. A better estimation of the same can be obtained by plotting the void volume as function of resistance change, since the later case eliminates the approximation introduced in the criterion of 5 element deletion per iteration. The simulated void volume variation as a function of resistance change is shown in Figure 5.5 and it is found that for the present case $V_c = 1.8 \times 10^{-21} \text{ m}^3$ and this value is found to be close to the void volume ($1.3 \times 10^{-21} \text{ m}^3$) obtained from physical failure analysis assuming a cylindrical void.

FIG. 5.4: Resistance change profiles.

FIG. 5.5: Increase of void volume as a function resistance change.

The physical meaning of the constant S (in Eq. (5.1)) can be explained using the concept of atomic concentration variation during EM mass transport in the following manner. The EM failure time (t_f) can be expressed as [26]:

$$t_f = \sum_{i=1}^m \frac{N}{AFD_i} \ln\left(\frac{N}{N_v}\right) = N \ln\left(\frac{N}{N_v}\right) \sum_{i=1}^m \frac{1}{AFD_i} \quad (5.6)$$

where N is the equilibrium atomic concentration and N_v is the atomic concentration in the depleted volume at time t_f . AFD_i is the average AFD of the depleted volume in the i^{th} iteration, and m is the total number of iteration.

On the other hand, using Eq. (5.3), one can re-write t_f as:

$$t_f = \sum_{i=1}^m \sum_{e=1}^5 \frac{S}{\bar{v}_e \times AFD_e} = \frac{S}{\bar{v}_e} \sum_{i=1}^{5m} \frac{1}{AFD_{avg,i}} = \frac{S}{\bar{v}_e} \sum_{i=1}^u \frac{1}{AFD_{avg,i}} \quad (5.7)$$

where $\bar{v}_e$ is the average volume of the element, and $AFD_{avg,i}$ is the average AFD for 5 elements that possessing of the top 5 AFD values. m is total number of iteration with 5 elements deletion at one iteration as described earlier. Since Eq. (5.6) is written for the single element deletion at each iteration, $u=5m$.

Comparing Eq. (5.6) and (5.7), the constant S can be written as:

$$S \approx \bar{v}_e N \ln\left(\frac{N}{N_v}\right) \quad (5.8)$$

The factor $\bar{v}_e N$ in Eq. (5.8) is the total number of atoms exists in each depleted element that form part of the void, and the later factor $\ln(N/N_v)$ is the criteria to delete an element. In our work, $\bar{v}_e \sim 10^{-23} \text{ m}^3$, and $N \sim 10^{28} \text{ atoms/m}^3$. With $S \sim 10^{13}$ as obtained above, $\ln(N/N_v)$ comes out to be $\sim 10^8$. In other words, an element can be deleted only if the atomic concentration in the depleting element is below $\exp(-10^8)$ of N instead of 10% as was proposed by Dalleau et al. [26]. Thus in the present case, the deletion criterion represents almost zero percent atomic concentration in the voided volume which is more realistic than the criterion of 10% atomic concentration in the voided volume.

From Eq. (5.8), we can see that the sample-to-sample variation in the failure time at a given EM stress condition can be due to the variation of $\bar{v}_e N$. This variation may be due to the various density of defects in interconnects from sample-to-sample, thus rendering different value of N . Another reason for the variation in failure time can be due to the variation in the sample-to-sample via diameter which is about 5% in a well qualified and established fabrication process. This is because the EM degradation is very sensitive to the via diameter for given line width. Hence the variation in the sample-to-sample failure times is expected.

5.4.2 Void evolution and AFD variation

It is found that the void occurs in the M1 metallization underneath the cylindrical via. The evolution of void is shown in Figure 5.6. It is noticed that the void initiation does not occur underneath the cylindrical via. But it initiates at the inner

FIG. 5.6: Void evolution (represented by darker area) is shown here. Void size (a), (b), (c) and (d) correspond to iteration number 2, 6, 9 and 13 respectively.

corner between the M1 metallization and cylindrical via and then progress toward external corner between the M1 metallization and cylindrical via.

For example, the total AFD distribution obtained in the 6th iteration is shown in Figure 5.7 and the value of AFDs for selected 5 elements (which will be deleted for the next iteration) is listed in Table 5.1. The variation of AFDs during void evolution is shown in Figure 5.8. From this figure, it can be seen that the stress gradient induced driving force is dominating at the beginning of the void formation while in the later part of the void evolution, EWF dominates. Although magnitude of AFD from temperature gradient induced driving force is found to be about one order less compared to other two AFDs, the terms associated with temperature gradient cannot be ignored, since equations of AFD for all three driving forces contains temperature gradient term (see Eq. (3.7)-(3.9)).

FIG. 5.7: AFD (number/m³-sec) distribution at 6th iteration.

Table 5.1: AFD values for selected 5 elements at the end of 6th iteration.

AFD @ EWF (number/m ³ -sec)	AFD @ Stress gradient induced driving force (number/m ³ -sec)	AFD @ Temperature gradient induced driving force (number/m ³ -sec)	AFD @ Total (number/m ³ -sec)
1.85E+30	4.33E+30	9.27E+29	7.11E+30
1.82E+30	4.26E+30	9.11E+29	6.99E+30
1.73E+30	3.98E+30	8.59E+29	6.57E+30
1.44E+30	3.13E+30	6.97E+29	5.27E+30
1.56E+30	2.32E+30	7.34E+29	4.61E+30

From the variation of AFDs with time (see Figure 5.8) one can predicts that, EM life-time can be improved by reducing the stress gradient induced driving force.

FIG. 5.8: Variation of AFDs as a function of time.

On the other hand, it is anticipated in previous chapters that by reducing the SFT of the structure, AFD from stress gradient induced driving force can be reduced. Thus by reducing the SFT, EM life-time can be improved which is indeed observed experimentally as discussed in chapter 4.

5.5 Summary

The CDFM is extended for dynamic EM study and EM degradation physics is presented for submicron Cu DD line-via structure. Critical void volume is estimated from model which is then compared with the same obtained from experiment and a good correlation is found. It is also shown that the stress gradient induced driving force and EWF dominates at the beginning and at the later part of the EM failure process respectively.

Chapter 6

IMPACT OF CURRENT CROWDING AND LINE WIDTH DEPENDENCE ON EM

6.1 Introduction

In chapter 3, it is anticipated that the difference in the EM characteristics in the case of line-via structure for two line widths should be governed by EWF due to the occurrence of current crowding. This fact is anticipated for the case when the via diameter and the EM stress condition are identical for both line widths.

Current crowding is obvious when current detours from its original direction. Thus current density becomes highly non-uniform for a bent electrical conductor [100-105]. In a bent conductor carrying electrical current, the peak current density occurs at the inner corner of the conductor [100-105] and hence increasing the EWF localized to current density peaks. On the other hand the median-time-to-failure (t_{50}) is related to stress current density (j) through the semi-classical Black's relation given by [10]

$$t_{50} = BWj^{-n} \exp\left(\frac{E_a}{k_B T}\right) \quad (6.1)$$

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where, B is constant, W is the line width and n is the current density exponent. The other symbols have their usual meaning.

There are numerous examples available today in support of the Eq. (6.1) and significant deviations are also predicted from this simple relationship [101-105]. Thus in a bent conductor such as in a line-via structure, due to the non-uniform distribution of the current density, deviation in Black's relation is expected.

Though current crowding in Al-based line-via structure was studied in 1990s [76], studies on current crowding for Cu-based metallization are hardly found. It is to be noted here that the cylindrical via (which connects the M1 and M2 lines) is an integral part of the M2 metallization for Cu based DD line-via structure and which is not true for case with Al-based metallization.

It is the purpose of this chapter to investigate the EM characteristics of two different line widths considering Cu DD line-via interconnects. The line width considered in this study is in the range of 0.28 μm to 0.7 μm . The impact of current crowding and its line width dependency on EM performance is presented. It is shown that the simple line width dependence concept does not hold for the present case and modified Black's equation is presented based on the experimental results.

6.2 Experimental

6.2.1 Sample fabrication

Cu line-via EM test structure (see Figure 3.8(a)) is fabricated for the present study using standard 0.18 μm Cu/oxide dual damascene technology. These samples are fabricated at Institute of Microelectronics, Singapore. A note on the sample preparation is given in Appendix II. The test line is 800 μm long, 0.35 μm thick and the via diameter is 0.26 μm for all the cases. The test lines are 0.28 and 0.7 μm wide and will be termed as narrow line-via and wide line-via structure respectively in this chapter.

6.2.2 EM test and physical failure analysis

Package level accelerated EM tests are conducted. The failure criterion was set to 10% increase in resistance. The EM test conditions with EM test results are summarized in Table 6.1.

Failure analysis was performed using FIB-SEM tool. Figures 6.1 and 6.2 are the failed sample micrographs of narrow and wide line-via structure respectively. It is observed that for both line widths, failure occurred in the M1 metallization at the bottom of the cylindrical via.

Table 6.1: EM test conditions and t_{50}

Width (μm)	Test Temperature ($^{\circ}\text{C}$)	Current Density (MA/cm^2)	t_{50} (hrs)	Log-normal sigma (ϵ)	Remarks
0.28	300	0.8	414.8	0.81	Wide line-via structure failed faster than narrow line-via structure
	325		280.2	0.60	
	350		189.4	0.33	
0.7	300		315.4	0.78	
	325		203.3	0.61	
	350		132.9	0.29	

The line width dependence is summarized in Figure 6.3. The cumulative density functions (CDFs) of the EM failures are shown in Figures 6.4 and 6.5 for narrow line-via and wide line-via structures respectively.

6.3 Simulation on current density distribution

In order to obtain the quantitative current density distribution in Cu DD line-via interconnects, a three dimensional coupled field finite element model by coupling electric and temperature fields is implemented. The model is similar to first phase model described in chapter 3. The test current density ($0.8 \text{ MA}/\text{cm}^2$) and temperature (300°C) are applied as boundary conditions in the model. The material properties are taken from ref. [63] for the present model. The current density distributions for narrow and wide line-via structures are shown in Figures 6.6 and 6.7 respectively.

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FIG. 6.1: SEM image of a failed narrow line-via sample. The EM stress temperature and current density were 350°C and 0.8 MA/cm^2 .

FIG. 6.2: SEM image of a failed wide line-via sample. The EM stress temperature and current density were 350°C and 0.8 MA/cm^2 .

FIG. 6.3: Line-width dependence at various test temperature.

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FIG. 6.4: EM failure distributions in the case of narrow line-via structure.

FIG. 6.5: EM failure distributions in the case of wide line-via structure.

FIG. 6.6: Current density (MA/cm²) distribution in narrow line-via structure.

FIG. 6.7: Current density (MA/cm²) distribution in wide line-via structure.

6.4 Results and discussion

To ensure the equal electrical stressing, which is proportional to applied current density rather than the current, both structures were tested with same current density, though the total current in the wide line-via structure will be 2.5 times higher of that in the narrow line-via structure at the same current density level.

From the CDF plots in Figures 6.4 and 6.5, one can see that there is significant variation of the ‘log-normal sigma’ (ϵ) with stressing temperature. As significant difference in ϵ implies different failure mechanisms, one should expect the activation energy (E_a) of EM is different at different test temperatures.

However, it is interesting to note that, the ϵ ’s are very close for the two line widths at a given test temperature. Since it is reported that E_a vary with line width [72], and with the close ϵ values observed between the two line widths, one should expect that their E_a difference should be small.

In order to determine the difference in E_a , the value of E_a can be estimated using the data from the two test temperatures of 300 and 325°C. This E_a can be viewed as the mean E_a in the temperature range of 300 to 325°C. The E_a values obtained are 0.48 and 0.52 eV for the narrow and wide line-via structures respectively. Hence, the difference in E_a is only 0.04 eV, which is indeed small as expected. From the E_a values calculated, one can see that the failure is interfacial diffusion dominated [68,106].

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Note here that the test data from 350°C is not used for the above-mentioned calculation of E_a because its ε value is too much different from that at 300°C. Hence, its inclusion in the average E_a computation could render a large error.

Under a high current density ($\sim \text{MA}/\text{cm}^2$), it is reasonable to assume that Cu/Ta or Cu/SiN interfaces are the dominant diffusion path. The average activation energies found earlier do suggest that the Cu interface/surface is indeed the dominant diffusion path.

On the other hand, since the thickness of Ta barrier is 25 nm in the present case, it acts as a perfect blocking boundary to the Cu atom flow between M1 and via [107] (see Figure 6.2). Thus, the interface diffusion can only occur at the interface between M1 line and the cap layer near the via zone or at the interface between M1 line and Ta via bottom barrier, and the failure is in essence a line EM failure.

The via bottom is identified experimentally as the failure location for both the line width structures at the Cu/Ta or Cu/SiN interfaces in the M1 line. As can be seen in Figures 6.6 and 6.7, the magnitudes of the average current densities along the interfaces of Cu/Ta or Cu/SiN near the via bottom for both structures depend on the line width. It can be computed that the average current density for the narrow line-via structure is 1.7 times the current density in the M1 line (Figure 6.6), and it is 4.9 times the M1 line current density in case of wide line-via structure (Figure 6.7).

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The higher ratio of the average current density along the interfaces mentioned above for the wide line-via can be understood as follows. As the line current density is the same for the structures, the total current is higher in the wide line-via structure. However, the via diameter is the same for all the structures, and thus the current is much crowded in the wide line-via structure. This renders the average current density to a higher ratio over the current density in M1 line, and making the current crowded zone more vulnerable to failure.

From Eq. (6.1), the ratio of t_{50} for narrow to wide line-via structure is given by

$$\frac{t_{50}^{narrow}}{t_{50}^{wide}} = \left(\frac{W^{narrow}}{W^{wide}} \right) \left(\frac{j_{int}^{narrow}}{j_{int}^{wide}} \right)^{-n} \text{Exp}\left(\frac{\Delta E_a}{kT}\right) \quad (6.2)$$

where the superscript “*narrow*” and “*wide*” corresponds to the narrow and wide line-via structure respectively. The subscript “*int*” refers to the interface current density at the line/via bottom interface, and ΔE_a is the difference in activation energies of the narrow and wide line-via structures which is found to be -0.04 eV as computed previously.

In order to estimate n , Eq. (6.2) is evaluated using the simulated current density at test temperature at 300°C with n varying from 1.8 to 2.0. It is found that $n = 1.9$ for the t_{50} ratio in Eq. (6.2) agrees well with the experimental data and this value of n is well within the reported value [72]. With this value of n , the t_{50} ratio at

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other test temperatures are computed, and the results are summarized in Table 6.2.

One can see an excellent agreement between the simulation and experimental results.

Table 6.2: EM test data analyses

Stressing Temp.	Ratio of $\frac{t_{50}^{narrow}}{t_{50}^{wide}}$ from experiment	Ratio of $\frac{t_{50}^{narrow}}{t_{50}^{wide}}$ using Eq. (6.2) with $n=1.9$
300	1.33	1.33
325	1.38	1.38
350	1.43	1.42

On the other hand, if the t_{50} ratio using Eq. (6.2) is computed without considering the current crowding, we will have the factor $\left(\frac{j_{int}^{narrow}}{j_{int}^{wide}}\right)^{-n}$ equal to 1 as line current densities are the same for both the structures. For example, the case where the test temperature is 325 °C, the median-time-to-failure ratio will be 0.18 which is far from the experimental observation. Hence, this study implies that the uniform line current density cannot be used to estimate the t_{50} for line-via EM, and indeed the current crowding effect affect the t_{50} significantly. The average current density along the interface at line/via bottom should be used to compute the t_{50} for EM in line-via structure under consideration.

6.5 Summary

The failure time for wide line-via is found to be shorter as compared to narrow line-via at identical EM test condition due to the effect of current crowding. From 3D finite element analyses and experimental data, it is shown that the uniform line current density is inappropriate for the estimation of t_{50} for EM in the line-via structure, but

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the width dependence Black's equation with average current density along the line/via interface provides an excellent approximation for the t_{50} .

Chapter 7

CONCLUSION AND FUTURE WORK

7.1 Conclusion

Several extrinsic EM weaknesses are identified for submicron copper interconnects. It is shown that surrounding materials and their processing history have paramount impact on EM degradation. A combined driving force model to explore EM failure physics is developed using finite element method. The model combines electron-wind force, force from stress gradient and force from temperature gradient. These three driving forces are shown to be comparable to each other at EM test condition. The finite element model computes driving forces and atomic flux divergences for above-mentioned driving forces.

The sources of the various driving forces are the non-uniform distribution of current density, temperature and stress. The non-uniformity in current density, temperature and stress field are obvious due to the presence of surrounding materials. Non-uniformity in these fields is also arises due to the structural inhomogeneity especially, in line-via structure where the two-level metallization is connected by via.

The above-mentioned non-uniform fields are the causes for existence of atomic flux divergence sites which in turn is the cause of mass depletion or accumulation. Thus the combined model developed here identifies the extrinsic weakness against EM mass transport.

From the static coupled field analysis, many conclusions can be drawn. In many cases of EM in Cu dual damascene interconnects, the model predicts the failure site correctly. For example, in narrow EM line test structure (of line width down to 100 nm), the model predicts that failure should occur near the bottom Cu/Ta interface instead of top Cu/cap interface. This fact is verified by line EM experiments. Also, for Cu line-via EM case, the model predicts the failure site correctly. In all cases, it is shown that at the very beginning of EM mass transport, force from stress gradient dominates over the other two driving forces.

It is identified that by reducing the SFT of the test structure, the AFD from stress gradient induced driving force can be reduced. As AFD is inversely proportional to failure time, hence by reducing the SFT, EM life-time can be improved. EM experiments are conducted to obtain relationship between SFT and median-time-to-failure and good correlation is obtained with the same from model.

A dynamic EM model based on driving force approach is presented. The model predictions are found to agree well with experimental results. This model is a physics-based model and computes the critical void volume, resistance change profile, AFDs etc. for a given structure.

It is shown that current crowding is a dominant factor for Cu line-via test structure. A wide line-via interconnect failed faster than that of a narrow one under identical EM stress condition. This is due to local effect such as current crowding. It is shown that for line-via interconnections; instead of considering uniform line current density approximation in Black's equation, the local current density at the via bottom holds a better approximation. For such line-via EM, a modified Black's equation is proposed.

7.2 Future Work

In this thesis we have developed and laid the groundwork on a combined driving force model to explain EM failure physics. Although the model explains many experimental facts however, it is by no means exhaustive, and from our point of view, more work still need to be further studied.

7.2.1 Modification of model

The drawback of the model is that it does not include the stress relaxation during EM mass transport, though this is not important for the static modeling but it may be important for the dynamic EM modeling. In the dynamic modeling, the void is assumed to be empty of material but relaxation in metallization stress field due to the occurrence of void is not considered. If this relaxation is considered, we believed that stress gradient induced driving force may not be important as soon as a tiny void formed in the metallization.

Though the CDFM developed in chapter 3, explains several experimental observations regarding the void locations in the line-via EM tests, other effects such as the low-k dielectric instead of SiO_2 , consideration of adhesion properties between Cu and SiN, the interconnect length effect etc. will be an interesting study.

The annealing condition to reduce the SFT is not optimized in this study. It is necessary to optimize the annealing condition for better EM performance. In doing so, it is to be kept in mind that sample resistance should not increase due to the additional annealing, since there is chance of stress-migration for annealing at high temperature (about 250°C) for long time.

The dynamic model is lacking from the actual time scale. Presently an arbitrary unit for time is used. By finding suitable approximation to the Eq. (5.1), the model can be manipulated to a physical time unit. For this purpose, in-situ EM experiment may be useful.

7.2.2 Modification in test structure

The resistance change during EM test is very sharp for the existing line-via structure. This is because there is a lack of current flow path as soon as a void covers the bottom area of via in the M1 line and hence a minute void volume is required for failure to occur. This problem can be solved to some extent by using gouging via. In a gouging via, the cylindrical via penetrates into the M1 line up to a certain depth. As a result, a better contact between the M1 line and the via is expected over the

conventional line-via structure. A schematic of the M1 line in case of gouging via is shown in Figure 7.1. In this figure, g_d represents the gouging depth.

FIG. 7.1: Schematic of M1 line in case of gouging via. Only one half of the line is shown here for better clarity.

The gouging via can be fabricated by intentional over etch during the via hole etching step in the damascene process technology. The critical void volume is expected to be much higher in case of gouging via in comparison to conventional line-via structure, since there will be electrical conduction path even if voids covers the area underneath the via in M1 line and hence improving the EM reliability. Application of dynamic CDFM to such gouging could be interesting.

Author's Publications

1. *Electromigration in damascene copper interconnects of line width down to 100 nm*, **Arijit Roy**, Rakesh Kumar, Cher Ming Tan, Terence K. S. Wong and C.-H. Tung, Semiconductor Science and Technology, Vol. 21, pp. 1369-1372 (2006).
2. *Probing into the asymmetric nature of electromigration performance of submicron interconnect via structure*, **Arijit Roy**, Cher Ming Tan, Thin Solid Films, Vol. 512, pp. 3867-3874 (2007).
3. *Effect of test condition and stress free temperature on the electromigration failure of Cu dual damascene submicron interconnect line-via test structures*, **Arijit Roy**, Cher Ming Tan, Rakesh Kumar, Xian Tong Chen, Microelectronics Reliability, Vol. 45, pp. 1443-1448 (2005).
4. *Experimental investigation on the impact of stress free temperature on the electromigration performance of copper dual damascene submicron interconnect*, **Arijit Roy**, Cher Ming Tan, Microelectronics Reliability, Vol. 46, pp. 1652-1656 (2006).
5. *Electromigration in ULSI interconnects*, Cher Ming Tan, **Arijit Roy**, Materials Science and Engineering: R: Reports, Article in press.
6. *Current Crowding Effect on Copper Dual Damascene Via Bottom Failure for ULSI Applications*, Cher Ming Tan, **Arijit Roy**, A. V. Vairagar, Ahila

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- Krishnamoorthy and Subodh G. Mhaisalkar, IEEE Transactions on Device and Materials Reliability, Vol. 5, No. 2, pp. 198-205 (2005).
7. *Investigation of the effect of temperature and stress gradients on accelerated EM test for Cu narrow interconnects*, Cher Ming Tan, **Arijit Roy**, Thin Solid Films, Vol. 504, pp. 288-293 (2006).
 8. *Effect of vacuum break after the barrier layer deposition on the electromigration performance of aluminum based line interconnects*, Cher Ming Tan, **Arijit Roy**, Kok Tong Tan, Derek Sim Kwang Ye, Frankie Low, Microelectronics Reliability, Vol. 45, pp. 1449-1454 (2005).
 9. *Effect of Current Crowding on Copper Dual damascene Via Bottom failure for ULSI Applications*, **R. Arijit**, C. M. Tan, V. V. Anand, K. Ahila, G. Zhang and M. G. Subodh, Proceedings of the 11th International Symposium on the Physical and Failure Analysis of Integrated Circuits, IEEE, pp. 173-176 (2004).
 10. *Extrapolation of Electromigration Accelerated Test Data for Submicron Interconnect Via Structure*, **Arijit Roy**, Cher Ming Tan, presented in ICMAT 2005 (International Conference on Materials for Advanced Technologies, Singapore).
 11. *Stress Migration Reliability of wide Cu Interconnects with Gouging Vias*, Y. K. Lim, **R. Arijit**, K. L. Pey, C. M. Tan, C. S. Seet, T. J. Lee and Vigar, Proceedings of 43rd Annual International Reliability Physics Symposium, IEEE, pp. 203-208 (2005).

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Appendix I

Line EM sample preparation

Cu/oxide damascene conductors of line-widths 100 nm and 150 nm and length of 500 μm are fabricated using specially designed alternating-phase-shift-mask with alternating phase shifted scatter bars to improve the lithographic resolution of Nikon S203 KrF deep ultraviolet lithography step and scan system. The trenches are formed using TEL DRM system by reactive ion etching. A top view CD-SEM image of 100 nm nominal wide trench is shown in Figure AI.1.

FIG. AI.1: Top view CD-SEM image of a trench with nominal CD of 100 nm.

Formation of Cu metallization in these trenches involved deposition of a stack of 15 nm Ta barrier by sputtering and a 50 nm Cu seed layer by self-ionized plasma-induced physical vapor deposition (PVD) in Applied materials PVD/CVD Endura HP 5500 without vacuum break followed by 500 nm electrochemically plated (ECP) Cu layer using Novellus SABRE system. The CMP process is controlled to yield 200 nm thick Cu metallization. In order to remove the native oxide (if any) on the Cu top surface, wafers were subjected to NH_3 plasma treatment before the cap layer deposition and then transferred to cap layer deposition without breaking the vacuum of the chamber. A 50 nm thick SiN layer is then deposited after the CMP process to serve as Cu cap layer followed by deposition of a layer of 300 nm undoped silicate glass. In a similar way, interconnects of AR=5 also has been fabricated. Critical dimension (CD) measurement by SEM was conducted after the CMP process. Figure AI.2 is showing CD measurement for a 100 nm wide and a 150 nm wide line. The cross section images obtained by TEM of the patterned interconnect is shown in Figure AI.3.

FIG. AI.2: SEM images of CD measurement for line EM sample after CMP process.

(a) 100 nm nominal width, (b) 150 nm nominal width.

The electrical resistances of the interconnect is measured at 40GHz and 26°C using Cascade Microtech probes (Infinity) and HP8510C Network Analyzer. The interconnect resistivity is then computed from the sample resistance data and its cross sectional area measured using high resolution TEM images. The resistivities of the 100 nm and 150 nm wide Cu lines are found to be 2.02 and 1.83 $\mu\Omega\text{-cm}$ respectively.

The average temperature coefficient of resistivity (TCR) in the temperature range of 26 to 325°C is over a large sample size (more than 40) and is found to be $2.8 \times 10^{-3}/^\circ\text{C}$.

The CD-SEM measurement, cross section measurement and electrical resistivity measurement of the patterned lines as discussed above implied a well controlled process for fabricating damascene Cu line interconnects.

FIG. A1.3 . TEM cross sectional images of (a) 100 and (b) 150 nm wide lines.

Appendix II

Line-via EM sample preparation

Line-via test structure of line-widths of 0.28 and 0.7 μm and length of 800 μm are fabricated using 0.18 μm Cu/oxide DD technology. The first inter-metal dielectric (IMD) stack consisted of 50 nm of PECVD SiN and 800 nm undoped silicate glass (USG) on top of p-Si substrate using Novellus concept two Sequel Express PECVD system. M1 trench was patterned using 248 nm lithography system and the USG layer was etched using a fluorine-based dry-etch chemistry in TFL 85 DRM oxide etcher. Photoresist stripping and wet clean were performed to ensure polymer residue-free trenches.

Formation of copper metallization in these trenches involved depositing a stack of 25 nm Ta barrier and 150 nm copper seed by physical vapor deposition (PVD) in Applied materials PVD/CVD Endura HP 5500 followed by 0.6 μm electrochemically plated (ECP) copper layer using Novellus SABRE system. A 50 nm thick SiN layer was deposited after CMP process to serve as copper cap layer. In our process a conventional ammonia plasma treatment was performed in order to remove native oxide from the top of the copper metallization surface just before the cap layer deposition and then wafers were shifted for cap layer deposition without breaking the chamber vacuum. After the cap layer deposition, layers of 800 nm USG, 50 nm SiN

and 500 nm USG were deposited as IMD-2 in which 50 nm SiN serve as trench-2 stop layer. Via and M2 trench were then formed by a via-first DD process. The M2 (lines connected to pads) were short so that voids would be expected to form in M1 only. The lines are of 0.35 μm thick and the via diameter (connecting M1 and M2 lines) is 0.26 μm . All wafers were annealed at 360°C for 30 minutes as a final process step.

The top view micrograph of a fabricated sample is shown in AII.1. The image is taken after the removal of the top oxide and nitride layers from the diced wafer.

FIG. AII.1: A top view micrograph of the fabricated sample.