Study on the effectiveness of reservoir length in improving electromigration in Cu/Low-k interconnects

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**Study on the Effectiveness of Reservoir Length in
Improving Electromigration in Cu/Low-k Interconnects**

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SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

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Summary

Electromigration (EM) occurs in the form of void formation because of mass transport, reducing the electrical reliability of interconnects. The aggressive shrinkage of interconnects while maintaining at high current capability and reliability emerges EM to be a serious reliability issue, especially with the introduction of Cu and low-k dielectric material in the backend integrated circuits. Reservoir region can contribute better EM reliability of interconnects. However, the effectiveness of the reservoir effect in improving EM reliability as a function of line width has not been studied. In this work, experimental studies on the reservoir effect of EM reliability are performed for the Cu/low-k dual-damascene interconnects with varied reservoir lengths in both narrow and wide metal lines. Finite element simulation is applied to assist us in understanding the mechanism of reservoir effect effectiveness.

Three-level EM test structures with various reservoir lengths in both narrow and wide metal lines are designed and fabricated with 65 nm Cu/low-k dual-damascene process. Inline electrical measurement and defective scanning show good quality of the samples. The EM results demonstrate that the wide metal line has approximately three times longer MTF than the narrow metal. It is also found that MTF is improved as the reservoir length increases from 0 μm to 0.05 μm , and there is no significant enhancement beyond the critical reservoir length of 0.05 μm in both narrow and wide metal lines. Furthermore, the maximum MTF enhancement factor is 1.72 in the narrow line, whilst it is only 1.28 times for the wide metal, indicative of better effectiveness of reservoir effect on EM for

the narrow metal line. The variation of the reservoir effectiveness as a function of the reservoir length is found to be different for different line width.

The effective reservoir volume concept is proved to be insufficient to explain the experimental results because the supply of atoms will not be limited by the effective reservoir volume in the wide metal line. The maximum atomic flux divergence (AFD) concept is used to explain the experimental results with good agreement. We found that the distance from the maximum AFD location to via corner (length of AB) has significant effect on the EM lifetime in the Cu interconnect. The larger reservoir enhancement rate in the narrow metal is mainly because the maximum AFD sites decrease from two to one as reservoir length increases, and thus the void growth rate decreases. For the case of the wide metal line, the reservoir length is much smaller than the distance from via center to metal edge in the width direction. This explains the smaller effect of the reservoir length in enhancing EM lifetime for the wide metal line as observed experimentally.

From the maximum AFD concept, it is found that SiLK low-k interconnect with larger CTE has shorter MTF than the other low-k interconnects. The saturation trend of EM enhancement due to reservoir length is also observed for different low-k ILD interconnects. Current density variation is found to be not important for EM improvement, while stress temperature can highly impact the interconnect lifetime and thus the enhancement factor. The temperature and thermo-mechanical stress divergence are found to be the dominant factors to influence EM lifetime.

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Chapter One

Introduction

1.1 Motivation

Electromigration (EM) has been intensively studied over decades. It is generally described as diffusion-controlled mass transport in metallic materials that is driven with high electrical current density ($\sim 1 \text{ MA/cm}^2$) [1]. Because of the mass transport of metal atoms from one point to another, it will render accumulation of vacancies or atoms in the metal line, and therefore it results in open or short circuit failure.

With products becoming more highly integrated and running at higher speed, interconnect dimensions shrink aggressively which make the metal cross-sectional area progressively smaller with technology, driving higher current density in interconnects, rendering EM as the primary reliability issue in the VLSI circuits [2-4]. Copper (Cu) has replaced Aluminum (Al) as the interconnect metallization due to its lower resistivity, higher melting point and intrinsically higher EM resistance [2,3] since $0.18 \text{ }\mu\text{m}$ technology and beyond. Owing to the higher requirement on RC delays of integrated circuits, low-k inter-level dielectric (ILD) has replaced traditional dioxide in Cu interconnects. The softer low-k dielectric materials, such as fluorine-doped silicon dioxide ($k = 3.5 \sim 3.9$) [5], carbon-doped silicon dioxide ($k = 2.8 \sim 3.2$) [6], and porous SiLK Resins ($k = 2.2$) [7] can expand more, conduct less heat and yield smaller

capacitance [8] than dioxide ($k = 3.9$). The technological benefits of Cu/low- k are quite clear but the full reliability impact is still being studied with great interest.

EM has been widely studied in various ways from physical test structures, such as interconnect length [9,10], width [11,12], multi-via structure [12,13] and so on. The reservoir region is referred as the extended length and/or areas and/or volumes of metal from the vias [14-19]. EM lifetime of interconnects can be prolonged by the reservoir region, which is called “reservoir effect”. Reservoir effect was early studied in AlCu interconnect with W via [14]. The mechanism was reported that voids generally initiated at the W/Al interface in the downstream EM test would move toward lower level of stress and vacancy concentration in the longer reservoir region. Reservoir effect was also observed in Cu dual-damascene (DD) structure [15-19]. Shao et al. [15] and Gan et al. [16] found that voids nucleated in the Cu/Si₃N₄ interface would move opposite to the direction of electron flow and then agglomerate to create a large void in the reservoir region. Finite element analysis conducted by Tan et al. [18] showed that thermo-mechanical stress gradient induced migration is the dominant driving force for void nucleation and growth in the reservoir region.

As interconnect line width is continuously shrinking, it is important to examine if the reservoir effect remains as effective as the line width decreases. However, few studies on the reservoir effect are known to date for metal line width scaling down to 100 nm. There is also no report on the correlation between the effectiveness of the reservoir effect and line width. Therefore, the objective of this work is to experimentally investigate this

effectiveness in the Cu/low-k interconnects with various reservoir lengths for both narrow and wide interconnects.

At the same time, a better understanding on EM mechanism in the reservoir structures is needed by developing accurate lifetime models. Finite element analysis (FEA) has become important in recent years, which is a powerful computer-based tool to model EM performance. The constructed EM model will be discretized into a finite number of “elements” and “nodes” and the characteristic of each individual node and element can be determined by the piece-wise approximation from the mathematical model. This finite element modeling will be helpful to clarify the mechanism of reservoir effect in the sub-micron Cu interconnects.

1.2 Objectives

Driven by the above motivations, the objectives of this project are described as below

- 1) To study the reservoir effect of EM in Cu/low-k interconnects experimentally with different line widths.
- 2) To perform finite element modeling for better understanding of the reservoir effect as a function of line width.

1.3 Major Contribution of the Thesis

This thesis work is aimed to study the effectiveness of reservoir length in improving EM lifetime of Cu/low-k metallization. The major contribution of the thesis is summarized below:

- (1). Experiments are carried out on test structures with different reservoir lengths for 65 nm Cu/low-k interconnect. EM results show that there is a saturation reservoir length at around 0.05 μm present in improving EM lifetime in both narrow and wide metal lines. It is also found that the reservoir effect is more effective for the narrow metal line.
- (2). Effective reservoir volume concept is proved to be insufficient to explain this experimental work since the supply of atoms will not be limited by the effective reservoir volume in the wide metal line.
- (3). Maximum atomic flux divergence concept is developed to clarify the experimental results with good agreement for both narrow and wide metal lines. We identify that the distance from the maximum AFD location to via corner has significant effect on the EM lifetime in the Cu interconnect.

(4). From the maximum AFD concept, it is found that SiLK low-k interconnect with larger CTE has shorter MTF than the other low-k interconnects. The saturation trend of EM enhancement due to reservoir length is also observed for different low-k ILD interconnects. Besides, stress temperature is showed to be one of the key parameters that influence the EM reliability. The different temperatures that induce thermo-mechanical stress divergence difference are the dominant reason to influence EM lifetime and reservoir efficiency.

1.4 Organization of the Thesis

In this project, the effectiveness of reservoir effect in improving EM in Cu/low-k dual-damascene structures has been investigated from experiment and simulation approaches. This thesis contains five chapters. Chapter one is the introduction of the thesis, including motivation, objectives, contribution and organization. Literature reviews on the area of EM physics, reservoir effect and finite element simulation are presented in Chapter two. Chapter three presents the experimental work from EM test structure, Cu dual-damascene fabrication process and EM test method. Inline electrical characterization and defect scanning results are summarized in this chapter. Then statistical analysis on the EM test data and physical failure analysis on the failed samples are also discussed. Chapter four is devoted to study the mechanism of reservoir effect of EM from two approaches, namely the effective reservoir volume concept and the maximum atomic flux divergence concept. Finally, Chapter five summarizes the results of this work and gives recommendations for future work.

Chapter Two

Literature Review

2.1 Physics of Electromigration

Conventionally it is believed that EM is a mass transport phenomenon under the electron wind force. In recent years, other driving forces are found to be important in influencing the EM characteristics. Details are described in this section.

2.1.1 Diffusion Path Approach

2.1.1.1 Electron Wind Force

Traditionally, EM is thought to be diffusion-controlled mass transport phenomenon in metallic conductor due to electric current. This theory was firstly developed by Fiks in 1959 [20] and Huntington [21] in 1961 which described that thermally activated metal atom became essentially free to lattice and was affected upon two opposing forces, namely (a) electron wind force and (b) back stress force. When mass transport is significant during EM, it will lead to the formation of voids or hillock/extrusions in the metal interconnects. It can therefore result in either: 1) an open circuit if the void formed in the metal line becomes big enough to sever it; or 2) a short circuit if the extrusion

becomes long enough to serve as a bridge between the affected metal and another adjacent to it.

Figure 2. 1 EM driving force illustration

The electron wind force is due to the momentum exchange between moving electrons and metal atoms in the application of electric current. On the other hand, the back stress force arises from mass accumulation at the anode end of interconnect which is opposite to the direction of electron wind force as illustrated in Figure 2.1. The electron wind force moves metal atoms in the direction of electron flow, while the back stress force pushes the atoms in the opposite direction. In the steady state regime, the net atomic driving force is the sum of EM electron wind force and stress induced backflow force. The net driving force is given by [9]

$$F_{EM,net} = F_{ewf} - F_b \quad (2.1)$$

where the electron wind force and back stress force are defined by [9]

$$F_{ewf} = Z_{eff}^* \cdot e \cdot \rho \cdot j \quad (2.2)$$

$$F_b = \frac{\delta\sigma}{\delta x} \Omega \quad (2.3)$$

where Z_{eff}^* is the effective charge number, e is the fundamental electron charge, ρ is the resistivity, j is the current density, $\frac{\delta\sigma}{\delta x}$ is the back stress gradient, and Ω is the atomic volume. Therefore, by substituting equations (2.2) and (2.3) into (2.1), the EM driving force could be expressed as

$$F_{EM,net} = Z_{eff}^* \cdot e \cdot \rho \cdot j - \frac{\delta\sigma}{\delta x} \Omega \quad (2.4)$$

It is well-known that the atomic flux divergence (AFD) of metal atoms due to driving force is the basic requirement to cause void or hillock formation. Kumar [22] clearly proved that void nucleation occurs at the site of maximum positive atomic flux divergence experimentally. Failure occurs only when there is a non-zero AFD. At a given point in interconnect, amount of vacancies flowing in and out from this point is exact the same if the AFD is zero, and there will be no net mass transport. If AFD value is positive, there will be a mass depletion, while mass accumulation if AFD value is negative.

2.1.1.2. Blech Effect

Blech and his coworkers [9] in 1976 found that there is no EM mass transport when the conductor length is below a certain value ($\sim 30 \mu\text{m}$) at a given stress condition. In a confined metal line, EM induces accumulation of atoms at the anode and depletion at the cathode. The accumulation of atoms produce back stress force opposite to electron flow

direction, and increase the chemical potential of atoms (Al, Cu) to such a level so that further transport of the atoms to the anode is impossible. Once the back stress gradient balances the electron wind force, there will be no net mass transport. This phenomenon is known as “Blech effect”. The critical value $(jL)_c$, product of current density and line length, can be derived from equation (2.4) as below [9]

$$(jL)_c = \frac{\Omega \Delta \sigma}{Z_{eff}^* \cdot e \cdot \rho} \quad (2.5)$$

The length of the conductor below which EM mass transport does not occur, is called critical length, also known as “Blech length”. Recent studies on Blech length in the Cu/oxide and Cu/low-k interconnects [10,23] observe that $(jL)_c$ product in low-k interconnects is lowered due to mechanically weak low-k dielectric compared with oxide. With decreasing Ta barrier thickness, the product is also found to be smaller because of the reducing confinement [24]. Besides, the threshold product is also found to depend on the temperature of Cu interconnects [25] in the range of 260 °C - 330 °C.

2.1.1.3 Mass Transport Pathways

In this methodology, EWF is thought to be the main driving force for EM mass transport. The basic requirement of this approach is that one or more diffusion path dominating EM performance is present in interconnect. Typical EM mass transport pathways are bulk, grain boundary, grain, defect and surface diffusion as shown in Figure 2.2.

Figure 2. 2 Different diffusion paths: 1. Bulk; 2. grain boundary; 3.grain/bulk; 4.defect; 5.surface

[26]

The drift velocity of metal atoms can be based on the drift equation [27,28] which expressed as

$$v_d = \frac{D_{eff}}{k_B T} \cdot F_{ewf} \quad (2.6)$$

where atomic diffusion coefficient D_{eff} is given by

$$D_{eff} = D_0 \exp \left(-\frac{E_a}{k_B T} \right) \quad (2.7)$$

EM can occur through a number of different pathways such as surface, interface, grain boundary, pipe, and lattice diffusion. The various pathways can be expressed as [29]

$$Z_{eff}^* \cdot D_{eff} = Z_B^* \cdot D_B \cdot F_B + Z_D^* \cdot D_D \cdot F_D + Z_I^* \cdot D_I \cdot F_I + Z_S^* \cdot D_S \cdot F_S + Z_{GB}^* \cdot D_{GB} \cdot F_{GB} \quad (2.8)$$

where Z_{eff}^* is the effective charge number. The subscripts represent various diffusion paths. These diffusion paths are

B = bulk,

D =dislocation,

I = interface,

S = surface,

GB = grain boundary

F_j (j = B, D, I, S, G) is the fraction of atoms diffusion through a given pathway, which depends on the geometry of interconnect. Each participated pathway has different Z^* value because electron wind force varies according to local electronic environment. At temperature less than 400 °C, the contribution of bulk can be negligible, and therefore only dislocation, interface, surface, and grain boundary pathways contribute EM failure [29]. Dislocation is always related on process. Fischer et al. [1] establishes a strong correlation of EM failure with local defects from processes such as liner deposition, pre-clean, or trench etching. Surface migration is reported to be dominant in 10 μm wide polycrystalline Cu lines for stress temperature less than 250 °C [28].

Activation energies for different metallization are shown in Table 2.1. Different activation energies are associated with each diffusion paths. Smaller activation energy means easier diffusion pathway. Cu shows higher activation energy than Al conductor. Grain size, impurity and texture of Cu are known to be critical factors in determining interconnect qualities such as film resistivity and EM resistance. Bulk activation energy of Cu metallization is larger than that of Al or Al/Cu alloy metallization. However, it is also reported that the range of activation energy is from 0.7 eV to 2.3 eV [29-32]. For

copper interconnects, the activation energy is typically 2.3 eV for bulk diffusion, 0.9 to 1.2 eV for grain boundary diffusion, and 0.8 eV to 1.0 eV for interface diffusion.

Metallization	Activation energy (eV) for various diffusion paths			
	Bulk	Grain boundary	Surface	Interface (typical)
Al	1.4	0.6	NA	?
Al/Cu (alloy)	1.2	0.7	NA	0.9–1.0
Cu	2.1	1.2	0.7	0.8–1.2

Table 2. 1 Activation energies for different metallization system [33]

Two interfaces exist and play an important role for atoms diffusion, namely Cu/dielectric interface and Cu/barrier interface. The effective drift velocity of Cu atoms during EM in Equation (2.6) can be re-written as [28]

$$v_d = \left[\left(\delta_{GB} \left(\frac{1}{d} \right) D_{GB} Z_{GB}^* + \delta_c \left(\frac{1}{h} \right) D_c Z_c^* + \delta_l \left(\frac{2}{w} + \frac{1}{h} \right) D_l Z_l^* \right] e \rho j / (k_B T) \quad (2.9)$$

where subscripts c and l denote the Cu/cap interface, and Cu/liner interface, respectively, d, h and w denote the average grain size, metal line thickness and width, correspondingly, and δ is the width of the interface.

If grain boundary is the major diffusion path for atom migration, grain and grain boundary orientations, or the texture can strongly influence the void evolution. Grain boundary triple points are observed as active flux divergence by in-situ microscopy study on Cu film [11]. For Cu metallization, Chang et al. [34] reported that 0.2 μm ~0.6 μm wide lines has near-bamboo grain structures, while 1.43 μm ~2.25 μm wide lines are

polycrystalline as shown in Figure 2.3. In the deep submicron regime, Cu conductor can possess more bamboo-like microstructure so that contribution of mass transport of EM along grain boundaries is negligible due to the lack of continuous grain boundary paths. Therefore, interfaces between Cu/cap and Cu/barrier play more important role in EM drift velocity in Equation (2.9). EM performance will be improved if the metal width or thickness is increased.

Besides, the choice of barrier material and seed layer quality can strongly affect the Cu microstructure and therefore the EM resistance. The grain structure and impurity content of deposited film can especially relate on electroplating conditions and sub-sequential annealing procedure.

Figure 2. 3 FIB images of the grain structures in the (a) 0.2, (b) 0.6, (c) 1.43, and (d) 2.25 μm wide lines. [34]

From the Equation (2.9), if the Cu/Ta interface diffusion is dominant, then the drift velocity becomes dependent of line width and thickness. However, diffusivity at Cu/Ta interface is believed to be slower than that at the Cu/cap interface [28]. Recent experiment studies [35-38] in the Cu interconnect show that EM is dominated by the Cu/dielectric interface among all of these diffusion paths. The Cu/dielectric interface is weak and consequently provided the fastest path for mass transport. Several methods have successfully suppressed the interfacial diffusion along the dominant Cu/dielectric cap interface path. Lin et al. [37] proved that SiCN cap layer has two times longer lifetime than SiN cap layer interconnects due to better interface adhesion. Hu et al. [38] reported EM lifetime of Cu interconnect can be improved a lot by selective electroless coating of CoWP, CoSnP or Pd on top of surface of Cu which was attributed to a reduction in Cu interface diffusion.

2.1.2 Driving Force Approach

As interconnect line shrinks to submicron level, the electron wind force approach is found to be no longer adequate to explain the EM phenomena as other kinds of driving forces may also become important. Rzepka et al. [39] prompted the development of driving force approach for EM study in 1999. Dalleau and Weide-Zaage [40] firstly presented that diffusion time of metal atoms or vacancies in interconnect is indirectly coupled with interacting fields such as current, temperature, stress and so on. Later, Tan and Roy [41] reported the presence of other driving forces besides the conventional electron wind force in the Cu interconnects. Finally, Tan et al. [41-43] conclude that three

combined driving forces in the EM model are the electron wind force (EWF), temperature gradient induced migration (TM) and thermo-mechanical stress gradient induced migration (SM) are capable to influence the EM characteristics. TM and SM are introduced and discussed below.

2.1.2.1 Temperature gradient induced migration(TM)

Atomic flux (AF) due to EWF is traditionally expressed as [41]

$$\vec{J}_A = \vec{v}_d \times N = \frac{ND_0}{k_B T} Z^* e \rho \vec{j} \cdot \exp\left(-\frac{E_a}{k_B T}\right) \quad (2.10)$$

where v_d is the atomic drift velocity, N is the atomic concentration, D_0 is the diffusivity factor, k_B is the Boltzmann's constant, T is the interconnect temperature, and E_a is the activation energy

Simillary, AF from TM can be given by[41]

$$\vec{J}_{th} = -\frac{NQ^*D_0}{k_B T^2} \exp\left(-\frac{E_a}{k_B T}\right) \nabla T \quad (2.11)$$

where Q^* is the heat transport, T is the local temperature and ∇T is the interconnect temperature gradient

Equation (2.11) shows that TM is proportional to the temperature gradient and heat transport. Atoms have tendency to move from a high temperature region to a low

temperature region, and thus temperature gradient leads atomic flow which in turn induces driving forces. Joule heating is the source of generating temperature gradient in interconnects. It exists during EM effect taking place and increases with time with the formation of void and hillocks. During void growth, the resistance of interconnect increases sharply which in turn increases the Joule heating. The non-uniformity distribution of temperature produces temperature gradient in interconnects. Besides, the available heat dissipation path and its effectiveness also play an important role to govern TM. As line thickness decreases, heat conduction through the dielectrics into the substrate increases dramatically, which is ignored in conventional formulation derivation.

EM test structure can also induce temperature gradient. For example, a test line with via has different Joule heating effect locally so that hot spot might exist. Lloyd [44] observed that EM failure location was always near the maximum temperature gradient and failure locations are distributed randomly at non-temperature-gradient areas. Nguyen et al. [45] performed experiment with built-in heating element in EM test structure and found that time-to-failure with temperature gradient of $0.0928 \text{ K}/\mu\text{m}$, $0.1928 \text{ K}/\mu\text{m}$, $0.28 \text{ K}/\mu\text{m}$ were correspondingly reduced to 90%, 40%, and 9% with respect to the time-to-failure without temperature gradient. They also observed voids near the site of maximum temperature gradient, consistent with the Lloyd's [44] experiment. Recently, Arnaud et al. [46] observed higher density of voids in the region of large temperature gradient in the Cu-based metallization.

2.1.2.2 Thermo-mechanical stress gradient induced migration(SM)

The AF due to SM is expressed as [41]

$$\vec{J}_s = \frac{N\Omega D_0}{k_B T} \exp\left(-\frac{E_a}{k_B T}\right) \nabla \sigma_H \quad (2.12)$$

where Ω and σ_H represent the atomic volume and hydrostatic stress.

The source of stress gradient is the non-uniform stress distribution due to thermal mismatch of the metallization material with its surrounding materials during EM stressing condition [47,48]. Li et al. shows that thermo-mechanical stress is the critical factor for void nucleation at the interface of the barrier layer and the grain boundary [43]. The thermo-mechanical stress that has an effect on EM is the same with the hydrostatic stress [30]. This thermo-mechanical stress gradient, can be anywhere in interconnect and arises from the beginning of EM test and is relaxed through void formation [30]. Thus, if this thermo-mechanical stress is not taken into account, the failure time will be overestimated.

The hydrostatic stress which is the source of stress gradient is given by

$$\sigma_H = \frac{1}{3} (\sigma_{11} + \sigma_{22} + \sigma_{33}) = -\frac{2E\Delta\alpha_1}{3(1-\nu)} (T - T_{SFT}) \quad (2.13)$$

where $\sigma_{11}, \sigma_{22}, \sigma_{33}$, are the stresses along the principal axes, E is the Young's Modulus, ν is the Poisson ratio, T is the EM stress temperature, T_{SFT} is the stress free temperature

(SFT) of interconnect, and $\Delta\alpha_1$ is the difference of the thermal expansion coefficient between interconnect metallization and the surrounding materials.

From Equation (2.13), one can see that the thermo-mechanical stress depends on interconnect SFT at which metallization remains free from stress and strain. The SFT of Cu interconnection is reported to be in the range of 350 °C - 400 °C [30], depending on the processing or annealing temperature during interconnect fabrication. Typically, EM stress temperature is at 250 °C – 350 °C in the oven for Cu metallization which is always smaller than the SFT. Thus, tensile stress exists in the conductor line and is distributed non-uniformly in the metallization. Geometry, non-uniformity of temperature distribution, surrounding materials and so on are the sources of non-uniform tensile stress [30]. Hence, one can expect a highly non-uniform stress field near the corner and edges of interconnects, and zones where different materials meet together.

Furthermore, fabrication process can also induce stress in the metal interconnect [41]. For example, Cu is deposited at room temperature while the cap layer is deposited at 400 °C. If this interconnect test structure is tested at 300 °C, there will be significant amount of stress that can lead to failure of interconnect or cause cap layer to crack. Also, the incorporation of several levels of metallization in current integrated circuit exposes interconnects to multiple thermal cycles, resulting in high tensile stress.

Due to tensile stress remaining in the metallization at EM test condition, EM lifetime improvement can be expected by lowering processing temperature. It is found that EM lifetime in interconnect with different processing temperature can be approximately five

times improvement by reduction of deposition temperature from 390 °C to 325 °C in interconnect lines [49]. This great improvement in EM performance is noticed due to the reduction of tensile stress gradient. However, further reduction in processing temperature such as 250 °C is not advised. This is because of poor dielectric quality with defects at such low processing temperature.

2.1.2.3 Atomic Flux Divergence (AFD) Distribution

EWF, TM and SM are taken into account as the driving forces for EM formula study. EM process linked to driving forces represents the amount of volume depleted or accumulated as a function of time by additional equations. The AFD can be derived from J_A , J_{th} and J_S in Equations (2.10) (2.11) (2.12) caused by EWF, TM, and SM.

The AFD due to electron wind force is given by [41]

$$div(\vec{J}_A) = \left(\frac{E_a}{k_B T^2} - \frac{1}{T} + \alpha \frac{\rho_0}{\rho} \right) \cdot J_A \cdot \nabla T \quad (2.14)$$

The AFD due to temperature gradient is given by [41]

$$div(\vec{J}_{th}) = \left(\frac{E_a}{k_B T^2} - \frac{3}{T} + \alpha \frac{\rho_0}{\rho} \right) \cdot J_{th} \cdot \nabla T + \frac{ND_0 Q^*}{3k_B^3 T^3} j^2 \rho^2 e^2 \exp \left(-\frac{E_a}{k_B T} \right) \quad (2.15)$$

The AFD due to hydrostatic stress gradient can be given by [41]

$$\begin{aligned}
div(\vec{J}_s) = & \left(\frac{E_a}{k_B T^2} - \frac{1}{T} \right) \cdot J_s \cdot \nabla T + \frac{2EN\Omega\alpha_1 D_0}{3(1-\nu)k_B T} \cdot \exp\left(-\frac{E_a}{k_B T}\right) \cdot \left(\frac{1}{T} - \alpha \frac{\rho_0}{\rho} \right) \cdot \nabla T^2 \\
& + \frac{2EN\Omega\alpha_1 D_0}{3(1-\nu)k_B T} \exp\left(-\frac{E_a}{k_B T}\right) \frac{j^2 \rho^2 e^2}{3k_B^2 T}
\end{aligned} \tag{2.16}$$

2.2 Reservoir Effect

Reservoir region is defined as the length and/or areas and/or volumes of metal from the vias. Reservoir region has low current density, low level of stress, and its presence can prolong the EM lifetime of interconnect, and such improvement is called “reservoir effect”. Many experimental works [14-19] for verifying reservoir effect have been published and all of them demonstrate that EM lifetime is dominated by reservoir length and number of vias. Reservoir effect was early studied in AlCu structure [14,50] with W via as inter-level connection as shown in Figure 2.4. EM lifetime was observed to depend on reservoir length in two different passivation dielectrics, flowable oxide (FOX) and high density plasma fluorinated silicate glass (HDP FSG) [50] in the downstream EM. Because reservoir region does not carry electric current during EM test, it is acceptable that the vacancy generation and annihilation does not occur in this region. Park and Jeon [50] believed that void formation at the reservoir region is because the vacancies would diffuse toward to low vacancy regions (or equivalently, Al atoms diffuse away from reservoir region). The better EM reliability of interconnect is thought to be the lower level of stress and vacancy concentration in the longer reservoir region.

Figure 2. 4 Schematic of multi-level Al-0.5%Cu test structure [50]

Reservoir effect was also observed in Cu dual-damascene structure [15-19], but the mechanism is different from that of W/Al structures. For Cu interconnects, the preferential void location is at the interface of Cu/dielectric cap layer which is mainly due to poor adhesion and thus high diffusion rate [35-38]. Shao et al. [15] studied the test structures with different reservoir lengths as illustrated in Figure 2.5 and found that MTTF could be doubled in the case of 60 nm extension than 0 nm extension and there is a critical reservoir length beyond which EM would not increase any more in Cu interconnects as shown in Figure 2.6. “Effective reservoir volume”, defined as low current density volume, was proposed to explain the EM lifetime enhancement by Gan et al. [16]. Longer extension length means larger effective reservoir volume, thus allows atoms accumulation and reduces the void formation rate to cause interconnects failure. Further increasing of reservoir length to 120 nm will not enhance reservoir volume and hence EM lifetime does not improved any further.

Figure 2. 5 Schematic of cross-sectional M2-via test structure [15,16]

Figure 2. 6 Cumulative Distribution Function (CDF) plot of median-time-to-failure for 280-nm-wide M2 copper lines with three different M2 extensions [15,16]

The FIB image of test structure after 10% resistance increasing showed that void nucleation takes place at Cu/Si₃N₄ interface away from cathode via [15]. Voids initiated at Cu/Si₃N₄ interface move opposite to the direction of current flow where they agglomerate to create a large void to block current flow through via, leading to an open circuit failure. Finite element analysis conducted by Tan et al. [18] showed that reservoir

length of 0.08 μm is the critical extension and thermo-mechanical stress gradient induced migration is the dominant driving force for void nucleation in the reservoir region. Stress can be released in the form of void nucleation and growth by diffusion. The reservoir effect is due to the movement of the maximum AFD sites with the reservoir length.

Besides, the numbers of reservoirs are reported to influence EM performance [19]. Single reservoir structure is observed to have significantly higher lifetime than that of the no reservoir structure due to the presence of back-stress to reduce the rate of atom migration. However, double reservoirs does not show much benefit with respect to no reservoir structure due to the increment in Cu limbs, which is described as a reduced impact from back stress in the double reservoir structure relative to the single reservoir case [19]. Also, reservoir effect due to via connecting matrix has also been studied and total area composed of vias and inter-space are identified as the key parameter to define the lifetime [51].

2.3 Finite Element Simulation

Finite element method is a numerical technique for finding approximate solutions of partial differential equations (PDE) as well as integral equations which are widely used in many areas, such as thermal, electromagnetic, fluid and structural working environment analysis. The methodology is in the way of discretizing the domain under investigation into a finite number of elements, and the characteristic of each element can be determined by the piece-wise approximations. In each individual element, equations are developed

on the basis of the governing equations from the mathematical model (e.g. PDE) by assuming a shape function to represent the physical behavior of an element. A popular and robust software available for FEA is ANSYS. Since EM is caused by diffusion under various driving forces coupled together, numerical methods have to be developed to solve the differential equations in 3-D coupled field.

In practical, a FEA in ANSYS consists of three principle steps:

1. Pre-processing: the geometry is constructed which will be sub-divided into a number of discrete sub-regions, or “elements”, connected at discrete points called “nodes”. Then select a suitable element type according to the analysis, where the underlying physics, mathematic equations, and finite element formulation are hidden in the element. Next, material properties are assigned, such as thermal conductivity for thermal analysis and Young’s modulus for stress analysis. Finally, apply boundary conditions and stress conditions to the model.
2. Solution: the dataset prepared by the pre-processor is used as the input to finite element code itself, which constructs and solves a series of algebraic equations
3. Post-processing: Check the validity of the solution results. Typical post-processor graphic displays overlays colored contours such as current density distribution, temperature distribution, and stress levels and so on.

The model for finite element analysis can be defined in both ANSYS Workbench and ANSYS Classic depending on the needs. There are various kinds of mesh methods, like tetrahedron, hexahedron and pentahedron (Figure 2.7). Tetrahedron and pentahedron

types of 3-D linear elements (4 nodes) are not recommended for thermo-mechanical analysis. It is compulsory to make each part of the model to be sweepable in order to obtain hexahedral mesh structure. The hexahedral meshing algorithm creates good quad mesh and is strongly recommended for finite element analysis of EM referenced from the literatures [40-43]. It is useful for bodies with large amount of interior volume and regular structure, but not helpful for thin complicated bodies where the ratio of volume to surface area is low. Thus, difficulties for hexahedral meshing arise if the model has irregular shape.

Figure 2. 7 Illustration of different element shapes

The element mesh size can be controlled. The smaller the size, the more accurate the results. However, a large model with too small mesh size could lead to higher computer hardware requirements and time consuming problem. ANSYS element library contains over 200 different element types which can be used for various kinds of studies. Solid 69,

solid 98 and solid 227 can be selected for 3-D thermo-electrical analysis for static EM as shown in Table 2.2. Solid 69 is special purpose for thermo-electrical with hexahedral mesh having 8-node structure, and an equivalent structural element solid 45 will replace solid 69 for thermo-mechanical analysis (Table 2.2) while the solid 98 and solid 227 are for quad tetrahedral mesh analysis. Solid 98 and solid 227 are capable to perform both thermo-electrical analysis and thermo-mechanical analysis, having up to 10 nodes with 3-D structure. The two elements have a quadratic displacement behavior and are well suited to the model with irregular shape. However, due to the midside nodes (see Figure 2.7) present during the tetrahedral mesh, simulation becomes more complicated and therefore it requires strong hardware capability.

Elements	Mesh Type	Thermo-Electrical	Thermo-Mechanical
SOLID 69	Hexahedral	v	
SOLID 45	Hexahedral		v
SOLID 98	Tetrahedral	v	v
SOLID 227	Tetrahedral	v	v

Table 2. 2 Elements used in coupled analysis

There are a few different solvers in ANSYS to support robust and comprehensive simulation and analysis capabilities to avoid problems such as memory error of the system. The basic kinds of solver are direct solver and iterative solver. The preconditioned conjugate gradient (PCG) solver, Jacobi conjugate gradient (JCG) solver and quasi-minimal residual (QMR) solver as shown in Table 2.3 are in the category of iterative solver. The advantages and disadvantages of different solvers are compared in

Table 2.3. Direct solver is based on a direct elimination of equations and it requires matrix factorization. Although it is more efficient and robust in solving equations, the large memory requirement is a gating problem. The solution from iterative solver is obtained through an iterative process that starts with an initial guess to a solution within an acceptable tolerance of the exact solution. This solver requires less memory and time per iteration than direct factorization. However, convergence of iteration methods is not guaranteed.

Solver	Advantages	Disadvantages
Sparse Direct Solver	Direct solver and produces very accurate solutions;	Large disk or in-core memory requirements
Preconditioned Conjugate Gradient (PCG) Solver	1. Iteration solver (starting with an initial guess solution for all DOFs); 2. About 4 to 10 times faster than the JCG solver for structural solid elements	1. Approximately twice as much memory as the JCG solver; 2. Convergence is not guaranteed
Jacobi Conjugate Gradient (JCG) Solver	Iteration solver and less memory is required	1. Slower processing than PCG solver; 2. Convergence is not guaranteed
Quasi-Minimal Residual (QMR) Solver		Not used for static analyses

Table 2. 3 Comparison among different kinds of solver

Chapter Three

Reservoir Length Effect on EM

3.1 Introduction

Three-level EM test structures with various reservoir lengths in both narrow and wide lines are designed and fabricated in 65 nm Cu dual-damascene process. In this chapter, experiment is conducted to investigate the reservoir effect of EM in both narrow and wide metal lines.

3.2 Experiment Setup

3.2.1 Sample Structure

A schematic diagram of the three-level EM test structure used in this study is shown in Figure 3.1. This kind of line-via structure is common for Cu-based metallization. To ensure that EM is properly assessed, the length of tested metal line (M2) is 400 μm , much longer than the critical Blech length. The feeder lines, M1 and M3, are designed to be wide and short metal line to avoid resistance effect on the test line M2 such that the EM induced void would be formed in the narrow and long test line (M2). In addition, dummy metal lines running parallel to the test metal (M2) with minimum space make the test

structure behave in a dense chip environment, and can help to minimize layout density variations. The line connecting to pad 8 is used to detect the leakage or extrusion failure. The structure allows Kelvin connections for resistance measurement by forcing the current and sensing the voltage.

Figure 3. 1 EM test structure layout illustration

Figure 3. 2 EM test structure side-view illustration

M2 extension/reservoir refers to the enclosure between M2 and V1 as shown in Figure 3.2 in this study. EM test structures with different reservoir lengths are designed to investigate the reservoir effect in Cu/low-k interconnects. Narrow (0.1 μm) and wide (0.3 μm) metal lines with various reservoir lengths of 0 μm , 0.03 μm , 0.05 μm , and 0.08 μm are designed as tabulated in Table 3.1. The tested metal line (M2) has a constant length of 400 μm with single via of diameter 0.1 μm . The downstream test is defined as a condition when the electrons flow from the upper wide metal line (M3) to the lower narrow metal line (M2) through the via (V2). The upstream test is defined as a condition where the electrons flow from the lower wide metal (M1) line through the via (V1) to the above narrow metal line (M2).

W/L	M2 Extension/Reservoir (μm)
0.1/400	0
0.1/400	0.03
0.1/400	0.05
0.1/400	0.08
0.3/400	0
0.3/400	0.03
0.3/400	0.05
0.3/400	0.08

Table 3. 1 Experiment split table

3.2.2 Sample Preparation

3.2.2.1 Sample Fabrication

Samples are fabricated with 65 nm technology node of Cu/low-k dual-damascene process on 300 mm wafers. Dual-damascene process is used to create the multi-level, high density metal interconnections for advanced, high performance ICs, as illustrated in Figure 3.3. In this methodology, wafers are patterned with photoresist (PR), and then anisotropic dry etch through hard mask (TiN). The hard mask is for afterward trench etch which can protect the below films from the PR stripping process, because low-k material formed ILD is susceptible to chemistries which might shift the k-value. The TEOS on top of ILD is to prevent ILD moisture absorption. The low-k film CoralTM ($k = 3.04$) is prepared by plasma-enhanced chemical vapor deposition (PECVD) by Novellus system. Then via etches down through the ILD and will stop at the embedded SiCN layer above Cu. If etching breaks through via hole to bottom Cu, it will sputter beneath Cu into the unprotected via hole sidewall. In this case, Cu will quickly diffuse into ILD, leading interconnect failure. Next, PR will fill via gap and etch back to form the trench with TiN as hard mask. After that, silicon nitride layer at the bottom of via is opened with low energy to avoid the underlying Cu sputtering into sidewall.

Figure 3.3 Cu dual-damascene process illustration

Next, Tri-layer barrier (Ta/TaN/Ta) is deposited by self-ionized plasma (SIP) technology in the Endura equipment, with the purpose of preventing Cu from diffusing into ILD or being oxidized during process. In addition, re-sputtering etching is important to reduce barrier overhang and leads to excellent sidewall coverage during barrier deposition. Then a Cu seed layer is deposited by PVD and followed by electroplating Cu in the bulk. This electroplating process has low cost, high throughput, and good via filling capability which also requires Cu seed layer smooth, continuous, and conformal along sidewall and at bottom of the vias. The excess Cu and liner films are removed using a chemical and mechanical polishing (CMP) process after annealing for half an hour to stabilize microstructure of electroplated copper. A thin silicon nitride layer is deposited on top of it, and then the dual-damascene structure is completed.

3.2.2.2 Sample Physical Structure

Transmission electron microscopy (TEM) has high imaging resolution and is widely used in semiconductor industry for physical analysis. The principle is that an electron beam is transmitted through an ultra thin sample, interacting with the sample as it passes through, and then image is formed from the interaction of the electrons transmitted through the sample. In order to make sure reservoir structures fabricated on the wafer, TEM is used to physically check the upstream EM test structure. The reservoir length is defined as the distance between via bottom and end of upper metal line as illustrated in Figure 3.4b. It shows that a longer reservoir length yields significant difference with a much steeper and fatter via shape in Figure 3.4. This can be explained that, for 65nm process, due to thin and soft ILD layer, sidewall ILD could also be etched during trench etching step. The longer reservoir length will let more ILD be removed. Although the layout dimension is not as exactly accurate as the fabricated structure, there is indeed reservoir length difference from this physical dimension check which could allow us to do further study on reservoir effect.

Figure 3. 4 TEM physical EM structure for the 0.1 μm metal line with reservoir length of (a) 0.03 μm; (b) 0.08 μm

3.2.2.3 Sample Quality Assessment

Inline electrical testing is important in the wafer fab to monitor process capability and stability. It can also reduce failure impact by detecting the abnormality of process or machine. Hence, in this work, electrical measurements are necessary to ensure that the actual EM experiments are conducted on wafer with good quality and to gain confidence on our EM experimental results. In this work, we only consider the sheet resistance (R_s) of tested metal line (M2) and metal via (V1) contact resistance (R_c) since upstream EM is mostly related on V1 and M2 quality. Long and continuous serpentine structure is integrated on the wafer to monitor R_s (Figure 3.5) while series via chain test structure is used to monitor R_c (Figure 3.6). R_s can be calculated by forcing a low magnitude of test

voltage (~1 volt) and sensing the current. Voltage is kept small to avoid Joule heating. R_c is the result of total measured resistance minus metal line resistance.

Figure 3. 5 Metal line sheet resistance test structure layout

Figure 3. 6 Metal via contact resistance test structure layout

Figure 3.7 shows the results of inline monitored R_s and R_c . The R_s has a mean value of 131 ohm/sq and standard deviation of 4.68. The sheet resistance is mainly influenced by the Cu electroplating and annealing process. The ratio of standard deviation to the average sheet resistance over large sample size (83 data points) is found to be 3.5%, which might be due to 12-inch wafer center-to-edge variation during fabrication. R_c has a mean value of 1.12 ohm/via and standard deviation over average contact resistance is

3.6%. Both R_s and R_c value are within the specification of the process, and process variation is less than 5%, indicating no abnormal effect on EM characterization.

Figure 3. 7 Inline measured (a) M2 sheet resistance (b) Via1 contact resistance

Defect scanning with KLA2800 with full-spectrum DUV/UV/VIS is also important to judge the wafer quality by defect capturing for all layers. Different kinds of defect, like PR remaining, Cu missing, Cu protrusion, can be detected. Figure 3.8 shows the defect results after cap layer deposition since there is no queue time concern at this step. The counted defect number is five. Defective die percentage is 0.101% in this wafer, demonstrating good quality of the samples.

Figure 3. 8 Defect results of (a) defect wafer map (b) defect percentage

3.2.3 EM Test

The Black equation is commonly used to predict median time-to-failure (MTF) of a group of identical conductor undergoing same EM stressing as following

$$T_{50\%} = Aj^{-n} \exp\left(\frac{E_a}{k_B T}\right) \quad (3.1)$$

where $T_{50\%}$ is the median time-to-failure, A is a material constant based on the microstructure and geometric properties of the conductor, j is the current density in the conductor, n is the current density factor, E_a is the activation energy, k_B is the Boltzmann's constant, and T is the stress temperature.

The expected lifetime of interconnect under operating conditions can be extrapolated from the Black's equation. Since high current density can induce Joule heating and high stress temperature causes larger thermal expansion mismatch, different failure mechanism may be rendered which increase uncertainty in extrapolating the test results.

Thus wafer level EM test has not been achieved widespread acceptance, and package level EM test should be performed with moderately accelerated temperature and current density for a long stress time.

In this package level EM test, wafer is diced, attached to a package and then wire bonding is connected on the individual pad. The packaged samples are placed on a built-in board, and then loaded in the ovens with EM stressing conditions. In this experiment, package level EM test is performed with stress temperature of 300 °C and current density of 2.1 MA/cm² to avoid excessive Joule heating on the metal line. Due to package level test having the disadvantages of time consuming, limited and expensive resources and most importantly, the purpose of the project is to study the reservoir effect, there is no need to collect the data at a few different stress conditions for the calculation of the activation energy.

A sample size of 25~30 is selected for each upstream EM test since void location in the downstream EM does not occur in the reservoir region. This will be further proved in this chapter. The failure criterion is defined as 10% increases from the starting resistance, or when the extrusion monitor current exceeds 1 μA.

3.3 Results and Discussion

3.3.1 Early Failure Analysis

For the narrow metal with reservoir length of 0.08 μm , from the failure distribution in Figure 3.9, the cumulative distribution function (CDF) plot is no longer lognormal and statistically bi-modal failure mechanism is suspected. The first failed sample is selected for failure analysis using focused-ion-beam (FIB) and TEM. FIB allows both cutting samples by gallium ion beam sputtering and imaging using ion-induced secondary electrons. The FIB nanometer-scale resolution allows it to choose the exactly thin region and also is commonly used to prepare samples for the TEM.

The failure site of the first failed sample is initiated in the middle of via as shown in Figure 3.10. This can be treated as early failure which is most probably caused by the process factors, such as via/metal etch process, Cu electroplating gap filling capability, barrier and seed quality, annealing efficiency and so on. One can observe from the TEM picture that there is a discontinuous point, almost at the same height with the void. This discontinuous point is at the intersection of via/ILD/cap layer which will induce large stress and accelerate EM failure during test. This process induced failure with short lifetime is taken as early failure.

Figure 3. 9 CDF plot for the narrow metal with reservoir length of 0.08 μm

On the other hand, for the late failure mode of EM effect, the failure location is always observed in the metal line as shown in the literature [12,36] and it is also observed in this work. The late failure mode will be discussed in the next section. Because reservoir effect is only related to metal line failure mechanism, we treat the first few samples as early failures and consider them as censored data so as to obtain actual lifetime related to the wear-out EM. With this consideration, the failure distributions of the samples are further analyzed by separating the data into two distributions. Data points are from the bottom of the distribution with short failure time, referred to “Type A”, while upper portion of the

distribution referred to “Type B”. The two distributions are fitted well by a single lognormal, as shown in Figure 3.9.

Figure 3. 10 Cross-sectional image of (a) FIB (b) TEM induced by EM for first failed sample of the narrow metal line with reservoir length of 0.08 μm

The weak mode refers to the lower portion of the distribution, occupying 25% of the failed samples, while the strong mode having a population of 75% at the upper portion of the distribution (Table 3.2). In the weak mode, smaller void size can cause via failure in terms of interconnect failure, and thus strong mode yields longer MTTF.

The lognormal sigma could reflect variations in several things, including the void location, shape and size to failure, sample variation due to manufacturing process variations (e.g. metal line dimension, via size, liner composition, liner thickness, cap deposition, and cap thickness), and stress condition variation [52]. Without separating the

data, the lognormal δ has a large value of 0.7, indicative of large sample variation and probably different failure mechanism. By considering the two distributions, smaller δ value is obtained, indicating smaller variations in individual distribution.

Group	Mode	Percentage	$t_{50}(\text{a.u})$	Sigma
All		100%	8.03	0.7
Type A	Weak	25%	3.01	0.215
Type B	Strong	75%	11.2	0.3

Table 3. 2 Strong and weak mode comparison

3.1.2 Late Failure Analysis

In order to understand the void behavior in the late failure mode, samples at different stress time are selected for physical failure analysis by FIB and TEM. Since reservoir effect is only related to the void formation in the metal line near the via [12,36], one needs to ascertain all the failures that we observed are of the same nature in order to have a meaningful study of the reservoir effect from the test data. The selected samples are in the group of the wide metal line with reservoir length of 0.03 μm and 0.08 μm . CDF distributions for this group are shown with well-fitted lognormal plot in Figure 3.11.

Figure 3. 11 M2 CDF plot for the wide metal line with reservoir length of 0.03 μm and 0.08 μm

The first failed sample with reservoir length of 0.03 μm has shortest failure time which has a smooth tapered via profile. The void occurs at reservoir/via region as shown in Figure 3.12. Even though EM failure time at 10% resistance increasing from the initial resistance is recorded, the EM test does not stop until the complete failure. However, due to the narrower path of the current conduction, current density increases rapidly in interconnect and the inner via/trench corner becomes a current crowding point in the subsequent EM test. Voids migration and morphological evolution occur under such condition, rendering that the void observed in the first sample is depleted slightly in the via.

Figure 3. 12 Cross-sectional FIB and TEM image induced by EM for the first failed sample for the wide metal line with reservoir length of 0.03 μm

The void for the second failure with reservoir length of 0.03 μm in Figure 3.13 is above the via and along the metal line, covering the reservoir region. The void dimension is observed to be wider in the Cu/cap interface which suggests that Cu/cap interface is indeed the fastest diffusion path, consistent with most of previous studies [35-38]. The void spans the whole reservoir region and finally causes interconnect failure.

Figure 3. 13 Cross-sectional FIB image for the second failed sample for the wide metal line with reservoir length of 0.03 μm

Void nucleated in the middle failure with reservoir length of 0.03 μm in Figure 3.14 is ~ 50 nm away from the cathode via, occupying the whole thickness of the metal line. Once void spans the whole thickness of the metal line, it has an additional interface with the Ta/TaN barrier, inducing significant Joule heating in the liner and leading finally to an open circuit. There might be a weak point (e.g. defect) at Cu/cap interface in the metal line, causing void nucleated location different from the others. Even though there are variations in void location for the late failure mode, it will not affect the accuracy on EM lifetime prediction because large sample size can fit a good lognormal distribution.

Figure 3. 14 Cross-sectional FIB image for the middle failed sample for the wide metal line with reservoir length of 0.03 μm

Void in the last failed sample with reservoir length of 0.03 μm in Figure 3.15 resides above the via along the metal line. Assisted with the high-diffusivity Cu/cap interface, the void dimension near the Cu/cap interface is larger than the dimension at bottom Cu/barrier interface, indicative of the Cu/cap interface fastest diffusion path. Besides, the void size is observed to increase with longer-standing stress time.

Figure 3. 15 Cross-sectional FIB image for the last failed sample for the wide metal line with reservoir length of 0.03 μm

Void in the middle failed sample with reservoir length of 0.08 μm in Figure 3.16 is also observed to be same with the previous cases in the reservoir region of metal line. It can be seen that EM void should be nucleated along Cu/SiN interface at the edge of the reservoir region and grow in the directions along the line length and thickness, resulting in fully spanning void in the metal line.

Figure 3. 16 Cross-sectional image for the middle failed sample for the wide metal line with reservoir length of $0.08\ \mu\text{m}$

For upstream EM test structure, via bottom is often reported as the early failure site due to process related defects [53] and it can be avoided by via process optimization [54]. Early failure at via bottom is not observed in this experiment, implying high quality of the sample fabrication process. The voids observed are always covering the reservoir region. Thus, the experimental data allows us to study the reservoir effect of this upstream EM test. In fact, this is the reason why only upstream EM test is conducted in this work since downstream EM failure location does not occur in the reservoir region as shown in the literature [12].

3.3.3 Width Effect on EM Performance

Figure 3. 17 CDF plot for the narrow and wide metal lines with reservoir length of (a) 0 μm , (b) 0.03 μm , (c) 0.05 μm , (d) 0.08 μm .

The CDF distributions between the narrow and wide metal lines are shown in Figure 3.17. They can be closely fitted using lognormal distribution, indicative of single failure mode in these structures. From Figure 3.17, one can also see that for the single via Cu structure used in this work, the wide metal has longer MTF as compared with the narrow metal for any reservoir length structures, in agreement with previous report [12]. The summary of t_{50} and lognormal δ is in Table 3.3.

W/L	Reservoir Length (μm)	t_{50} (A.U)	Sigma
0.1/400	0	6.50	0.59
0.1/400	0.03	9.50	0.50
0.1/400	0.05	11.09	0.41
0.1/400	0.08	11.20	0.30
0.3/400	0	24.93	0.49
0.3/400	0.03	25.55	0.57
0.3/400	0.05	31.94	0.50
0.3/400	0.08	31.99	0.42

Table 3. 3 Reservoir effect of EM summary table

It can be seen from Table 3.3 that for the single via Cu structure, the wide metal has almost three times longer MTF than the narrow metal, almost proportional to the line width for the upstream EM test. The experimental phenomenon can be explained from the effective drift velocity since EM lifetime is inversely proportional to the atoms drift velocity. The effective drift velocity of Cu atoms during EM in Equation (2.9) is expressed as below [28]

$$v_d = \left[\left(\delta_{GB} \left(\frac{1}{d} \right) D_{GB} Z_{GB}^* + \delta_c \left(\frac{1}{h} \right) D_c Z_c^* + \delta_l \left(\frac{2}{w} + \frac{1}{h} \right) D_l Z_l^* \right] e \rho j / (k_B T) \right. \quad (3.2)$$

Change et al. [34] reported that 0.2 μm ~0.6 μm wide lines had near-bamboo grain structures, while 1.43 μm ~2.25 μm wide lines are polycrystalline. For the narrow line width used in this experiment, grain boundary diffusion can be negligible in Equation (3.1) due to the absence of continuous grain boundary. Hence, EM performance is mainly contributed by the Cu/cap and Cu/liner interfaces. From Equation (3.2), the mass drift velocity is reduced as line width is increased, and therefore the wide metal line has better EM resistance than the narrow metal line.

As line dimension shrinks, critical void size for EM failure is also reduced. Hence, this longer MTF in the wide metal line is expected since a larger void size is needed to cause metal trench failure in the wide metal due to the absence of continuous grain boundary in the lines of width 0.1 μm and 0.3 μm [34].

3.3.4 Reservoir Effect on EM Performance

To study the line width dependence of the reservoir length effectiveness in improving interconnect EM lifetime, we examine the enhancement of t_{50} due to the reservoir length for structures with different line widths. The t_{50} enhancement factor M is defined as the ratio of the EM median time-to-failure (MTF) of reservoir structures to that of structures with no reservoir as following

$$M = \frac{MTF_{reservoir}}{MTF_{noreservoir}} \quad (3.1)$$

The MTF with no reservoir structure is used as a reference to normalize all other cases with varied extension lengths. With this definition, we have the experimental results as plotted in Figure 3.18 where the enhancement factor is always greater than one which confirms that an increase in MTF due to the presence of a reservoir.

It can be seen from Figure 3.18 that the MTF is improved as the reservoir length increases from 0 μm to 0.05 μm for the narrow metal line, and further increase in the reservoir length beyond 0.05 μm does not result in any additional improvement. Such saturation effect is also observed for the wide line as it can be seen in our results. Shao et al. and Gan et al. [15-17] reported that EM lifetime could be doubled when extension length increases from 0 μm to 0.06 μm and there is no EM lifetime enhancement from 0.06 μm to 0.12 μm . This experimental saturation effect is in good agreement the Gan et al. and Shao et al. previous report. In this work, we conclude that 0.05 μm is the critical reservoir length beyond which there is no further EM lifetime enhancement.

However, despite the common trend of enhancement factor with respect to reservoir length, there are some other important differences in our results and are not being reported previously. It is observed that the improvement in t_{50} due to reservoir length for the wide metal line does not occur until the length is 0.03 μm as observed in our experiments.

It is also interesting to note that the maximum MTF enhancement factor is 1.72 in the narrow line, whilst it is only 1.28 for the wide metal, indicative of better effectiveness of reservoir effect on EM for the narrow metal line. The mechanism of the effectiveness of reservoir length in improving EM lifetime depending on line width will be discussed in detail in the next Chapter. Also, the near-zero enhancement for the wide metal line in the range of 0 μm to 0.03 μm reservoir length has not been reported previously and it will be also explained in the Chapter four.

Figure 3. 18 EM t_{50} enhancement factor with respect to reservoir length

3.4 Summary

Experiments are conducted on the EM test structures with various reservoir lengths which are fabricated with 65 nm technology node of Cu/low-k dual-damascene process. Failure analysis reveals that the void formation is always in the reservoir region. The wide metal has longer MTF as compared with the narrow metal since a larger void size is needed to cause metal trench failure in the wide metal.

It is also found that there is a critical reservoir length of 0.05 μm , beyond which EM will have no further improvement in both narrow and wide metal lines as observed from experiment. The maximum MTF enhancement factor is 1.72 in the narrow line, whilst it is only 1.28 times for the wide metal, indicative better effectiveness of reservoir effect on EM for the narrow metal line. Furthermore, the improvement in t_{50} due to reservoir length for the wide metal line does not occur until the length is 0.03 μm as observed in our experiments.

Chapter Four

Mechanism of the Reservoir Length Effectiveness

4.1 Introduction

There are currently two schools of thought, namely the effective reservoir volume concept and maximum atomic flux divergence (AFD) concept to explain the reservoir effect. The concept of effective reservoir volume is that only part of the extension volume can supply atoms to reduce the rate of vacancies accumulation. For the AFD concept, it is based on the movement of the maximum AFD sites with the reservoir length that causes the observed reservoir effect. This chapter will investigate the mechanism of the effectiveness of reservoir length from the two concepts through finite element analysis.

4.2 Model

4.2.1 Methodology

The finite element (FE) model developed by Dalleau [40] and Tan et al.[41-43] from the driving force approach consists of two steady-state analysis, including a direct coupled analysis with current and temperature fields, and indirect coupled analysis between

temperature and stress fields. The methodology in this work used in the ANSYS is shown in the flow chart in Figure 4.1.

Figure 4. 1 Methodology of two stage simulation

Firstly, physical model must be constructed with the definition of dimension and material type. After meshing, a two-stage coupled field analysis is required in this work. In the first stage of analysis, the model is applied with EM stress current density and temperature, while the substrate of the model is kept at constant EM test temperature. From this stage, we could obtain the current density and temperature distributions and

also the individual nodal temperature. In the second stage of analysis, thermo-mechanical coupled analysis is applied with the following boundary conditions: a). individual nodal temperature from first stage analysis is applied as second stage nodal temperature; b). the substrate bottom surface is kept fixed and no displacement is allowed for the bottom surface of the substrate; and c). the vertical symmetric plane is constrained to remain vertical arising from the mirror symmetrical nature of the structure under consideration. In this way, hydrostatic stress distribution can be retrieved in the second stage simulation. From the current density, temperature and stress distributions, we can get AFD distribution from the AFD equations.

4.2.2 Model Description

4.2.2.1 Model Introduction

The finite element EM model is constructed to study the reservoir effect of EM as shown in Figure 4.2. Figure 4.3 only displays the Cu interconnect as a current conducting path by removing the surrounding materials. Strictly speaking, the via has steeper via sidewall as shown from the TEM pictures in Figure 3.4. Since hexahedral sweep mesh method could not be applied for irregular shape and also tetrahedral mesh method is not accurate to obtain results [40-43], the via is modeled as a cylinder to obtain perfect hexahedral mesh instead. Single layer of barrier is only considered in this model, even though tri-layer (Ta/TaN/Ta) of barrier is fabricated for the experimental structures. Barrier film can block Cu diffusion and this model assumes barrier films to be sufficient for good step

coverage and uniformity. Also, in view of the fact that the void nucleation site is located in the metal line and barrier shows superior confining ability in our experiment, we just consider single barrier in the model. Besides, the Cu interconnect is 400 μm long in this experiment, but only part of the length is considered in the simulation because void is located in the metal line near via from this experiment.

Figure 4. 2 Finite element model for the study on reservoir effect of EM

Figure 4. 3 Cu interconnect retrieved from finite element model

Four finite element models with different reservoir lengths of 0 μm , 0.03 μm , 0.05 μm and 0.08 μm are constructed in both narrow and wide metal lines. In the case of the narrow line width such as 0.1 μm , the difference between the via diameter and line width becomes very small, causing difficulties during meshing. For this reason, the narrow line width is selected to be 0.14 μm in the model. The dimensions of the present FEA models are shown in Table 4.1 which supports the geometry parameters measured from TEM physical dimension from Figure 3.4. This model is sliced into many sweepable bodies so as to obtain hexahedral mesh. Element solid 69 with hexahedral shape is selected for the

electrical-thermal coupled analysis, while solid 45 is used for the thermo-mechanical coupled analysis.

Feather	Size (μm)
M2 width(Narrow)	0.14
M2 width(Wide)	0.3
M2 thickness	0.21
Via diameter	0.1
Via height	0.12
Barrier thickness	0.01
Via bottom barrier thickness	0.005
Cap SiCN thickness	0.05

Table 4. 1 Model dimension list

4.2.2.2 Mesh Convergence Check

To avoid inappropriate mesh density impact on the final results, simulations are carried out at different mesh density with the same boundary conditions in the narrow metal line. A large mesh size with 0.1 μm is found to induce problematic meshing and it will result in failure. On the other hand, the hardware cannot support the simulation if the mesh size is less than 0.005 μm for this model. Hence, a suitable mesh density is quite important for us to perform further simulation. Figure 4.4 shows the minimum stress (compressive stress), maximum stress (tensile stress) and stress range with the increase of mesh density in the interconnect. A convergence point from the stress distribution is observed for the

mesh density at around 0.015 μm . Hence, from this analysis, a minimum element size of 0.015 μm is used throughout this work.

Figure 4. 4 Stress variation with mesh density, convergence achieved at around 0.015 μm

4.2.2.3 Material Properties

By virtue of the symmetry of the structure, only half of the model is simulated. The material properties are taken from the references [55-57] and listed in Table 4.2. These EM models are subjected to a current density of 2 MA/cm^2 and a stress temperature of 300 $^{\circ}\text{C}$. The SFT is set at 350 $^{\circ}\text{C}$ in this analysis where the difference between stress temperature and SFT is 50 $^{\circ}\text{C}$. Material properties, such as resistivity and thermal conductivity, are considered to be constant at different temperature in this simulation since they are weak dependent on temperature from the reference [58]. Low-k carbon

doped oxide (CDO) is doping SiO₂ with carbon to lower the dielectric constant to 3.0. The EM test structure in this work is fabricated with Novellus System Coral which also falls in this CDO low-k category.

Material	Young's Modulus (GPa)	Possion ratio	Thermal conductivity (W/mK)	Coefficient of thermal expansion (/°C)
Cu	110	0.34	379	18x10 ⁻⁶
Ta	186	0.34	53.65	6.3x10 ⁻⁶
SiN	220	0.27	0.8	3.2x10 ⁻⁶
SiO2	71.4	0.16	1.75	0.68x10 ⁻⁶
Low-k CDO	4.47	0.3	0.4	12.9x10 ⁻⁶

Table 4. 2 Material properties list [55-57]

4.3 Results and Discussion

4.3.1 Effective Reservoir Volume Concept

The effective reservoir volume [16] was proposed by Gan et al. to explain reservoir effect which is defined as the low current density region to supply atoms to reduce the rate of vacancy accumulation. Voids move opposite to the direction of current flow and towards to the cathode end via where they agglomerate to create a large void to block current flow through the via, leading to open circuit failure. Longer reservoir length can increase effective reservoir volume and hence it was the reason why EM lifetime is improved. As illustrated in Figure 4.5a, the effective reservoir volume is referred to the volume directly above the via (from line A to the right end of metal line) in M2 where current density within the volume is less than the cutoff current density. The normalized effective reservoir volumes for current densities in the range of 0.3-0.5 MA/cm² are plotted in Figure 4.5b. A critical current density is suggested to be 0.4 MA/cm², because the reservoir volume enhancement trend at 0.4 MA/cm² is in good match with the experimental behaviors as reported in the literature.

Figure 4. 5 (a) Metal/Via top view illustration (b). Normalized effective reservoir volume in terms of extension length [16]

In order to justify whether the effective reservoir volume is suitable to explain our experimental work, finite element analysis is applied to simulate the current density profile to study the effective reservoir volume enhancement. With the boundary conditions of stress current density in the metal line at 2 MA/cm^2 and temperature at 300°C , current density distribution can be retrieved directly in the first stage of thermo-electrical analysis.

Figure 4.6 shows the current density distributions (unit: $\text{pA}/\mu\text{m}^2$) for the narrow metal line at reservoir lengths from $0 \mu\text{m}$ to $0.08 \mu\text{m}$. All the test structures have the same current density scale, and it has been found that the lowest level of current density is always located in the reservoir upper corner region as illustrated in Figure 4.6. The low current density zone will change shape accordingly with the increment of reservoir length as observed.

Figure 4. 6 Current density distributions for the narrow metal at reservoir length (a) 0 μm (b) 0.03 μm (c) 0.05 μm (d) 0.08 μm

Besides, another low current density region at location B as shown in Figure 4.6 appears in the longer reservoir length structures. This is expected because the reservoir region is not an effective current conducting path and longer reservoir length definitely has larger volume with low current density. However, the effective reservoir volume does not refer to the low current density volume, because it does not consider the reservoir length

portion of the metal directly above the via. Therefore, the computation of the effective reservoir volume should be conducted.

The effective reservoir volumes at a series of different cutoff current density are calculated from the simulation. For a given cutoff current density, the effective reservoir volume at 0 μm reservoir length is used as a reference to normalize others with varied extension lengths. The normalized reservoir volume enhancement factor with respect to reservoir length is shown in Figure 4.7, in comparison with the experimental enhancement factor (the dash line).

For the cutoff current density larger than 1.4 MA/cm^2 as shown in Figure 4.7, the reservoir volume enhancement factor increases with reservoir length accordingly in the range of 0 μm $\sim$ 0.05 μm reservoir lengths. Saturation trend is observed for the effective reservoir volume enhancement between 0.05 μm and 0.08 μm . However, the effective reservoir volume enhancement factor is 1.1 in the narrow line, while it is 1.72 from the experiment. The much smaller factor suggests that this effective reservoir volume in the narrow metal is not sufficient to reduce vacancy accumulation speed to reach the same MTF enhancement efficiency as experiment. Also, in the range of 0.03 μm $\sim$ 0.05 μm reservoir lengths, effective reservoir volume increment is much slower than the experiment. Besides, at smaller cutoff current density of 1.2 MA/cm^2 , it does not show additional enhancement but a slight decrease. This is contradicted with the Gan et al. [16] report where the normalized effective reservoir volume can keep increasing all the time at smaller cutoff current density.

Figure 4. 7 Normalized effective reservoir volume in terms of reservoir length at various cutoff current densities in the narrow metal line

Current density distributions (unit: $\text{pA}/\mu\text{m}^2$) for the wide metal at reservoir lengths from $0 \mu\text{m}$ to $0.08 \mu\text{m}$ are shown in Figure 4.8 with the stress current density in the metal line at $2 \text{ MA}/\text{cm}^2$. The low current density zone in the wide metal line has same phenomena with the narrow metal line, and the reservoir volume becomes larger than the narrow metal line. Our EM test structure is single via connected, so that current in the wide metal is around twice of the narrow metal in order to keep same current density in the metal line. That is the reason why the whole via in the wide metal obtain higher current density than via in the narrow metal.

Figure 4. 8 Current density distributions for the wide metal at reservoir length (a) 0 μm (b) 0.03 μm (c) 0.05 μm (d) 0.08 μm

The reservoir volumes at a series of different cutoff current density are calculated from the simulation for the wide metal line. A saturation trend is also observed in the range of 0.05 μm and 0.08 μm reservoir lengths for cutoff current density larger than 1.4 MA/cm^2 from Figure 4.9, in agreement with the narrow metal line. However, at very small cutoff

current density ($J = 1.2 \text{ MA/cm}^2$), it also shows a decrease in effective reservoir volume. In addition, the mechanism with near-zero enhancement factor for the wide metal in the range of $0 \text{ } \mu\text{m}$ to $0.03 \text{ } \mu\text{m}$ reservoir lengths as observed cannot be explained with effective reservoir volume concept. Hence, as a conclusion, effective reservoir volume is insufficient to explain the experimental work.

Figure 4. 9 Normalized effective reservoir volume in terms of reservoir length at various cutoff current densities in the wide metal line

As illustrated in Figure 4.10, from the typical current density profile, the peak current density appears at the inner corner of via-top, resulting in high local current density at this corner. This high local current density produces strong electron wind driving force and hence affects the MTF from the Black's equation. However, FIB analysis does not show the failure directly located at the inner corner of via-top which suggests that current density is not the dominant factor for EM failure.

Figure 4. 10 Typical current density distribution for the EM test structure

4.3.2 Maximum AFD Concept

4.3.2.1 Driving Force Formulations

For the AFD concept, it is based on the fact that the diffusivity of vacancies in interconnects can result in atomic flux divergence and therefore form void or hillock. Tan [18] showed that it is the movement of the maximum AFD site with the reservoir length that causes the observed reservoir effect. In order to investigate if the AFD concept can be used to explain the reservoir effect, MultiphysicsTM coupled field finite element analysis (FEA) is applied for the present test structures to enhance our understanding on the mechanism.

As interconnect continues scaling, the conventional driving force formulation in the Chapter Two is reported to be no longer accurate in predicting void nucleation site. Tan [18] reported that when the metal line thickness decreases, heat conduction through the dielectric into the substrate increases dramatically. Compared to the conventional driving force Equations (2.14 – 2.16), the driving force formula [18] used in this work (4.1 - 4.3) considers also the vertical heat conduction through the dielectrics into the substrate. Also, no assumptions on the geometry of the structure is made in the thermo-electrical and thermo-mechanical analysis, unlike the conventional formula. The directions of the respective driving forces are also taken into consideration such that all the driving forces are represented as vector and their interactions are represented by the dot product. With the considerations, the AFD equations are as follows [18].

$$div(\vec{J}_A) = \left(\frac{E_a}{k_B T^2} - \frac{1}{T} + \alpha \frac{\rho_0}{\rho} \right) \cdot \frac{N}{k_B T} e Z^* \rho D_0 \exp\left(-\frac{E_a}{k_B T}\right) \cdot j \cdot \nabla T \quad (4.1)$$

$$div(\vec{J}_{th}) = -\left(\frac{E_a}{k_B T^2} - \frac{2}{T} \right) \cdot \frac{N Q^* D_0}{k_B T^2} \exp\left(-\frac{E_a}{k_B T}\right) \nabla T \cdot \nabla T - \frac{N D_0 Q^*}{k_B T^2} \exp\left(-\frac{E_a}{k_B T}\right) \nabla \cdot (\nabla T) \quad (4.2)$$

$$div(\vec{J}_s) = \left(\frac{E_a}{k_B T^2} - \frac{1}{T} \right) \cdot \frac{N \Omega D_0}{k_B T} \exp\left(-\frac{E_a}{k_B T}\right) \nabla \sigma_H \cdot \nabla T + \frac{N \Omega D_0}{k_B T} \exp\left(-\frac{E_a}{k_B T}\right) \nabla \cdot (\nabla \sigma_H) \quad (4.3)$$

4.3.2.2 Stress Distributions

To compute the AFD due to the above mentioned three driving forces, thermo-mechanical stress of each node is extracted from the structural analysis as shown in Figure 4.11 and Figure 4.12 (unit: MPa). Model with no reservoir length is not simulated owing to discretization problem as also reported in reference [42] for both narrow and wide metals. In the case of no reservoir length model, the width between via edge and metal line edge becomes very small which encounters hexahedral mesh problem and is hard for us to get accurate AFD results. Hence, the model without reservoir length is not considered in this work to compute the AFD. In the wide metal line, reservoir length with $0.015\text{ }\mu\text{m}$ structure is used to investigate the near-zero EM lifetime enhancement between $0\text{ }\mu\text{m}$ and $0.03\text{ }\mu\text{m}$ instead. Because the AFD value is also very sensitive to the mesh density, all of the structures are kept with same mesh density for comparison.

The maximum thermo-mechanical stress is located at the metal/dielectric/barrier interception point for all the structures. The resultant hydrostatic stress in the structure with reservoir length of $0.08\text{ }\mu\text{m}$ is the largest (about 80 MPa) in the narrow metal line, and this is much smaller than the Cu yield strength (which is around 280 MPa) [55-57]. At the Cu/dielectric interface, a larger stress is observed compared with Cu/barrier interface. This is expected because the thermal expansion difference between Cu/dielectric is larger than that of Cu/barrier interface as shown in Table 4.2. The stress changes from tensile stress, at the interface of Cu with surrounding materials, to compressive stress in the bulk Cu. This is because of large thermal mismatch between Cu and cap/barrier layers.

Figure 4. 11 Stress distributions for the narrow metal at reservoir length (a) 0.03 μm (b) 0.05 μm
(c) 0.08 μm

The stress distributions for the wide metal line are shown in Figure 4.12. The maximum stress in the wide metal is located at the Cu/cap/barrier corner and is comparable among different reservoir lengths structures. The small change in thermo-mechanical stress is due to the small increase in temperature.

Figure 4. 12 Stress distributions for the wide metal at reservoir length (a) 0.015 μm (b) 0.03 μm
(c) 0.05 μm (d) 0.08 μm

Different thermal expansion between metal and surrounding materials arises during fabrication. For example, hydrostatic stress is induced when the deposited nitride cap layer is cooled down to room temperature, and multi-thermal cycle during process can also induce large thermo-mechanical stress with several levels of interconnect. During EM testing, dissimilar material thermal expansion mismatch will build up hydrostatic stress again. The built-up hydrostatic tensile stress was then partially relaxed through the

formation and growth of voids [59]. Further relaxation of stress can be realized by either plastic deformation or diffusion. Since EM test temperature is at 300 °C in this work, thermo-mechanical stress is assumed to be released by diffusion, leading to an increased stress gradient induced driving force subsequently [18]. As this work only studies static EM, stress relaxation is not considered.

4.3.2.3 AFD Distribution and Discussion

Figure 4. 13 AFD distributions for (a) 0.03 μm, (b) 0.05 μm reservoir length in the narrow metal line

With the current density, thermal and structural analysis results obtained from ANSYS simulation, the AFD distribution of the model can be calculated based on the improved EM formulations. Since the void growth time is significant smaller than void nucleation

time, it is reasonable to assume that the void location is at the maximum AFD site during the nucleation stage [42]. Hence, modeling EM with AFD is sufficient to give us an understanding of the relationship between void location and EM stress conditions.

Figure 4.12 shows AFD distributions at the portion of interconnect near the via in the narrow metal. In the case of the test structure with reservoir length of $0.03\text{ }\mu\text{m}$ in the narrow metal (Figure 4.13a), two void nucleation sites are observed at the Cu/cap interface which can collapse into a bigger void to form a critical void after some time. However, as the reservoir length is further increased, the maximum AFD locations change to the upper and lower corner region (Figure 4.13b). Since the Cu/cap interface is the fast diffusion path, only AFD in the upper corner will be of concern. We believed that it is the change from two maximum AFD locations to one location that will enhance the EM lifetime of the narrow metal line significantly. A further elaboration is as follows.

Figure 4. 14 EM test structure top view for the (a) narrow metal and (b) wide metal with reservoir structure

Figure 4. 15 Maximum AFD with respect to the distance from point B to point A for the narrow metal line

Figure 4.14 shows the schematic top view of the metal lines. From Figure 4.14a, we can see that when the reservoir length is increasing, the distance from point B to point A will increase too, and the maximum AFD is becoming larger as can be seen in Figure 4.15 for the narrow line. Here point A is the edge of the via, and point B is the site of maximum AFD. As the maximum AFD represents the vacancies accumulation speed, the time for a void to grow to reach point A from point B is thus proportional to the distance between A-B over the maximum AFD as shown in Equation (4.4) below,

$$t \propto \frac{\text{distance}}{AFD_{max}} \quad (4.4)$$

Table 4.3 shows the value of the distance/ AFD_{max} in Equation (4.4) for the narrow metal line with different reservoir lengths. One can see that the lifetime increases with reservoir

length, in agreement to the experimental observation. Also, for reservoir length of 0.03 μm , there are two maximum AFD locations, and hence its MTF will be much smaller than those of reservoir lengths of 0.05 μm and 0.08 μm . From Table 4.3, we can also see the saturation of the lifetime enhancement when the reservoir length goes beyond 0.05 μm , and this is observed in our experiments.

Reservoir length (μm)	AFDmax (atoms/ $\mu\text{m}^3\text{s}$)	Distance/AFD _{max} ($\mu\text{m.s}/\text{atoms}.\mu\text{m}^3$)
0.03	1.98E+14	3.16E-16
0.05	2.64E+14	3.31E-16
0.08	3.82E+14	3.23E-16

Table 4. 3 MTF proportionality constant in the narrow metal

Figure 4. 16 AFD distributions for reservoir length of (a) 0.03 μm , (b) 0.08 μm in the wide metal

For the wide metal line, the situation is as shown in Figure 4.14b where the reservoir length is smaller than the distance between the via corner and the edge of interconnect

line. Thus the supply of atoms will not be limited by the effective reservoir volume as proposed by Gan et al. [16] and this may be the reason why the effective volume concept cannot be applied in our work.

In order to understand the reservoir length effect in the wide metal line, the 3-D AFD distribution in the wide line with reservoir length of 0.03 μm and 0.08 μm is shown in Figure 4.15. Maximum AFD location is observed near corner B, which is the same as that of in the narrow metal line. Table 4.4 shows the value of the distance/AFD_{max} for the wide metal line with different reservoir lengths. From Table 4.4, it is clear that there is almost no lifetime enhancement when reservoir length is below 0.03 μm . Similarly for the case of reservoir lengths from 0.05 μm to 0.08 μm , and this explains the saturation of the lifetime enhancement. Only when reservoir length increases from 0.03 μm to 0.05 μm , there is EM lifetime enhancement which is due to longer distance between points A and B as the reservoir length increases.

Reservoir length (μm)	AFDmax (atoms/ $\mu\text{m}^3\text{s}$)	Distance/AFDmax ($\mu\text{m.s/atoms}.\mu\text{m}^{-3}$)
0.015	2.74E+14	5.49E-16
0.03	2.76E+14	5.53E-16
0.05	2.49E+14	6.36E-16
0.08	2.76E+14	6.15E-16

Table 4. 4 MTF proportionality constant in the wide metal

From the previous investigation of the reservoir effect, we can understand that the distance from the maximum AFD location to via corner has significant effect on the EM

lifetime. Figure 4.17 plots the length of AB with respect to the reservoir length for metal lines with different reservoir lengths. From Figure 4.17, we can see that the length of AB increases faster and larger with reservoir length for the narrow metal line. With reference to Figure 4.14, it is easy to see that increasing the reservoir length has the effect of pushing the maximum AFD further from the via edge, and thus its reservoir effect is solely determined by the reservoir length. Furthermore, as the reservoir length increases, the maximum AFD sites decrease from two to one as discussed previously and thus the void growth rate decreases. In other words, the effect of the reservoir length on EM lifetime enhancement is expected to be larger in the narrow metal.

On the other hand, for the case of the wide metal line, the reservoir length is much smaller than the distance from via to metal edge in the width direction (less than 15%), and the length of AB increases slowly with the increase in the reservoir length as can be seen in Figure 4.17. Thus, it is not surprise to understand the smaller effect of the reservoir length in enhancing EM lifetime for wide metal line as observed experimentally. Also, as observed in Figure 4.17, the near-zero change in the length of AB for the wide metal line when the reservoir length is increasing from 0 to 0.03 μm further confirms the observed zero EM lifetime enhancement until the reservoir length goes above 0.03 μm .

Figure 4. 17 The distance from point B to point A with respect to reservoir length

4.3.3 Parameters Impact on Reservoir Effectiveness

Finite element analysis is employed to explore the lifetime enhancement factor with various low-k materials in the model to study the reservoir effect. Moreover, stress conditions of current density and temperature are also taken into account in the model with the maximum AFD concept approach in the further study. Because the maximum AFD sites decrease from two to one as reservoir length increases in the narrow metal, this renders difficulty to compare the real enhancement factor in the present study. Hence, only the wide metal with same failure mechanism will be carried out to investigate the parameters impact on the reservoir effect.

4.3.3.1 Low-k Dielectric Material Impact on Reservoir Effect

With the above findings, we extend our discussions to three low-k materials, namely SiCOH, SiLK and porous MSQ. The purpose is to examine if the low-k materials can impact the reservoir effect using the maximum AFD concept.

The material properties are taken from reference [55-57] and listed in Table 4.5. The finite element model is the same as Figure 4.1 with the same boundary conditions.

Material	Density (kg/ μm^3)	Young's Modulus (GPa)	Possion Ratio	Coefficient of Thermal Expansion (1/°C)
Cu	8.30E-15	110	0.34	1.80E-05
SiN	3.10E-15	220	0.27	3.20E-06
CDO	1.51E-15	4.47	0.3	1.29E-05
SiCOH	9.10E-16	16.2	0.3	1.20E-05
SiLK	9.00E-16	2.5	0.4	6.60E-05
Porous MSQ	9.80E-16	3.6	0.25	7.30E-06

Table 4. 5 Material properties list [55-57]

The distributions of thermal gradient are comparable for interconnects with different low-k materials as the Joule heating due to the stress current is identical for all the structures. However, the distributions of thermo-mechanical stress arising from thermal expansion mismatch are largely different with various low-k materials as shown in Figure 4.18 owing to the vastly different CTE of the materials. For example, one can observe that the smallest tensile stress is present at the Cu/cap interface and the largest compressive stress

is inside the Cu bulk for the SiLK low-k interconnect, whilst in the porous MSQ low-k interconnect, the tensile hydrostatic stress is the largest at the Cu/cap/barrier intersection point. Also, the distributions of hydrostatic stress in CDO and SiCOH low-k interconnects are similar with porous MSQ interconnects because of comparable

Figure 4. 18 Hydrostatic stress distributions in interconnects with different ILD materials (a) CDO, (b) Porous MSQ, (c) SiCOH and (d)SiLK. The reservoir length is 0.03 μm .

coefficient of thermal expansion (CTE) as tabulated in Table 4.5. It is also expected that a slightly smaller tensile hydrostatic stress is present at the Cu/cap/barrier intersection point for CDO and SiCOH low-k interconnects compared to the case for porous MSQ because CTE for CDO and SiCOH are closer to the CTE of Cu than the case of porous MSQ from Table 4.5, and all of them are having smaller CTE than Cu. However, the CTE of SiLK is more than five times larger than the other low-k dielectrics, and thus its distribution is totally different from the rest as expected.

The built-up hydrostatic tensile stress was observed to be partially relaxed through the formation and growth of voids [59]. The dominant driving force for Cu interconnect to influence its EM performance is found to be the thermo-mechanical stress gradient induced driving force which has been proven by many EM research works [18,30,41-43], especially for the performance with respect to the reservoir effect [60]. Hence, the maximum AFD induced by thermo-mechanical stress gradient driving force will be discussed in this work. The AFD induced by thermo-mechanical stress gradient migration in Equation (4.3) is given below [18].

$$\text{div}(\vec{J}_s) = \left(\frac{E_a}{k_B T^2} - \frac{1}{T} \right) \cdot \frac{N\Omega D_0}{k_B T} \exp\left(-\frac{E_a}{k_B T}\right) \nabla \sigma_H \cdot \nabla T + \frac{N\Omega D_0}{k_B T} \exp\left(-\frac{E_a}{k_B T}\right) \nabla \cdot (\nabla \sigma_H) \quad (4.5)$$

The strength of AFD from Equation (4.5) composes two factors, namely thermo-mechanical stress gradient and thermo-mechanical stress divergence. In this work, the AFD contributions by the two terms in Equation (4.5) at point B are calculated as shown

in Table 4.6 for Cu interconnect with different low-k materials. The Term 1 refers to the product of thermo-mechanical stress gradient and thermal gradient, while Term 2 is the effect of the thermo-mechanical stress divergence.

Materials	Stress Gradient	Temperature Gradient	Stress Divergence	Term1	Term2	Term 1 Contribution	Term 2 Contribution
CDO	3542	0.001336	302270	1.14E+08	2.74E+14	0%	100%
Porous MSQ	3750	0.001336	304529	1.20E+08	2.76E+14	0%	100%
SiCOH	3203	0.001336	291437	1.03E+08	2.64E+14	0%	100%
SILK	2156	0.001336	332464	6.91E+07	3.01E+14	0%	100%

Table 4. 6 Contributions of different sources on the total AFD. The reservoir length is 0.03 μm .

From Table 4.6, we can see that the Term 2 induced by thermo-mechanical stress divergence is around 6 orders of magnitude higher than the Term 1 induced by thermo-mechanical stress gradient and temperature gradient. This result suggests that thermo-mechanical stress divergence is the dominant contribution to the total AFD at different low-k interconnects to influence EM performance.

Figure 4. 19 Thermo-mechanical stress divergence distributions in interconnects with different ILD materials (a) CDO, (b) Porous MSQ, (c) SiCOH and (d)SiLK. The reservoir length is 0.03 μm .

The distributions of thermo-mechanical stress divergence with various low-k materials are shown in Figure 4.19. The maximum thermo-mechanical stress divergence value is always located at point B as denoted in Figure 4.19 which coincides with the maximum AFD position as expected. Among all the low-k dielectrics considered in this work, the SiLK ILD interconnect is associated with the highest thermo-mechanical stress divergence due to its very large CTE difference between SiLK and Cu. Also, it was reported that mass transport is dominated by diffusion at the Cu/cap layer interface, independent of ILD materials [61,62]. Hence, even if the thermo-mechanical stress divergence distribution in SiLK low-k interconnects is different from the rest, only point B at Cu/cap interface is taken into account. In short, the high CTE of various low-k dielectrics will impose significant challenges in the EM reliability for a given interconnect line dimension.

Figure 4. 20 Maximum AFD value with respect to the reservoir length in interconnects with different ILD materials

Reservoir Length	Stress	Stress Gradient	Stress Divergence
0.03	77.54	3542	3.02E+05
0.05	78.33	3620	2.54E+05
0.08	77.58	3617	2.61E+05

Table 4. 7 The simulated maximum stress, stress gradient and stress divergence near point B in the CDO low-k ILD interconnect.

With the above understanding, the maximum AFD values which represent the rate of void growth computed from the simulation are plotted in Figure 4.20. When reservoir length increases from 0.03 μm to 0.05 μm , the maximum AFD value shows a decrease because of smaller thermo-mechanical stress divergence value with longer reservoir length interconnect which is inversely proportional to the change in the thermo-

mechanical stress at point B as shown in Table 4.7. However, there is slightly an increase in AFD value compared with 0.05 μm reservoir length as it is further increased to 0.08 μm as expected because little reduction in the thermo-mechanical would increase the stress divergence to some extent. Moreover, SiLK interconnect is always observed to yield largest AFD value at any of the reservoir lengths and it is believed that it is the attribute to its high thermo-mechanical stress divergence and this will render a poor EM performance for SiLK interconnect. The higher thermo-mechanical stress divergence will drive atoms to move faster to accelerate interconnect failure during EM.

Figure 4. 21 The variability chart for MTF proportionality constant at different reservoir length for various low-k interconnects

Figure 4.21 shows the the value of the distance/AFD_{max} which is proportional to the MTF of an interconnect as we have established earlier. From Figure 4.21, one can see that interconnect with SiLK dielectric has lower MTF than others which is consistent with the experimental work conducted by Ho et al. [62]. It is found that the MTF in organic polymer/Cu interconnect which actually has comparable CTE with SiLK, is shorter than

the MTF in porous MSQ/Cu interconnect [62] under same test conditions. This smaller MTF is explained by a weak dielectric confinement effect where the low-k with higher CTE interconnect can reduce back-flow stress, resulting in an increase in net mass transport and a reduction of EM lifetime [62]. With this experimental supporting data, it is also not surprise to understand the reason why SiLK low-k interconnect has shorter MTF than the other low-k interconnect.

It is also interesting to note that the lifetime enhancement is comparable in the range of 0.03 μm to 0.05 μm for various low-k materials that is due to the enhancement of the length of AB and the reduction of the stress gradient divergence. Although the MTF enhancement in the CDO low-k interconnect has a slightly trend to decrease as further increased from 0.05 μm to 0.08 μm , our experimental observation with the same ILD material with this simulation confirms the saturation trend in this range of 0.05 μm ~ 0.08 μm . This indicates that low-k material does not change the phenomenon of the enhancement and saturation of lifetime. Further experimental works will be useful to verify this finding.

4.3.3.2 Effect of Current Density

Table 4.8 shows the maximum AFD summary at stress current density of 1.5, 2 and 2.5 MA/cm² for different reservoir lengths structures. It is found that the maximum AFD value does not vary with current density, and hence current density is not the major

source of EM lifetime enhancement, and this is expected as the reservoir effect is due to thermo-mechanical stress and not related to the current density.

Reservoir length (μm)	J (MA/cm²)	AFDmax (atoms/ μm³s)
0.03	1.5	2.76E+14
0.03	2	2.76E+14
0.03	2.5	2.76E+14
0.05	1.5	2.32E+14
0.05	2	2.32E+14
0.05	2.5	2.32E+14
0.08	1.5	2.76E+14
0.08	2	2.76E+14
0.08	2.5	2.76E+14

Table 4. 8 Maximum AFD value summary at different current density

4.3.3.3 Effect of Stress Temperature

The temperature gradient from simulation is the same for different stress temperatures due to comparable Joule heating induced by current density. However, hydrostatic stress distributions yield large difference with respect to temperature as shown in Figure 4.22. This is because of the difference in the materials expansion at different temperatures. The hydrostatic stress as given in Equation (2.13) is re-written here as follows.

$$\sigma_H = \frac{1}{3} (\sigma_{11} + \sigma_{22} + \sigma_{33}) = - \frac{2E\Delta\alpha_1}{3(1-\nu)} (T - T_{SFT}) \quad (4.6)$$

From the above equation, it is expected that lower stress temperature results in higher stress in the interconnection because of the larger difference between the stress temperature and the stress free temperature. When the stress temperature is equal to the stress free temperature, the interconnect is reported to be free from stress and strain [30]. In this work, stress free temperature is set at 350 °C. Figure 4.22 shows that hydrostatic stress is largest at 100 °C and near zero at 350 °C, as expected with the equation.

Figure 4. 22 Hydrostatic stress distributions for interconnects at stress temperature of (a) 100 °C, (b) 250 °C and (c) 300 °C and (d) 350 °C. The reservoir length is 0.05 μm .

The AFD induced by the thermo-mechanical stress gradient is expressed in Equation (4.5). Let us define the following parameters for further discussion.

$$\text{Constant 1} = \left(\frac{E_a}{k_B T^2} - \frac{1}{T} \right) \cdot \frac{N \Omega D_0}{k_B T} \exp \left(- \frac{E_a}{k_B T} \right)$$

$$\text{Constant 2} = \frac{N \Omega D_0}{k_B T} \exp \left(- \frac{E_a}{k_B T} \right)$$

$$\text{Term 1} = \text{Constant 1} \cdot \nabla \sigma_H \cdot \nabla T$$

$$\text{Term 2} = \text{Constant 2} \cdot \nabla \cdot (\nabla \sigma_H)$$

We have the values of the parameters as shown in Table 4.9. From Table 4.9, we can observe that thermo-mechanical stress divergence is the dominant factor to impact the total AFD at all temperature, consistent with the previous discussion on low-k materials. Hence, we will only focus on the AFD contribution by Term 2 in this work. As seen from Table 4.9, the Term 2 contribution is mainly caused by the constant 2 which increases rapidly with temperature, especially in the range of 100 °C ~ 200 °C. On the other hand, the thermo-mechanical stress divergence reduces with increasing temperature. Hence, we can say that at low temperature, thermo-mechanical stress divergence is dominant over the constant 2 value which is directly related to temperature. The changes of AFD contribution due to constant 2 and stress divergence with temperature is shown in Figure 4.23.

Temperature	Stress	Stress Gradient	Stress Divergence	Constant 1	Constant 2	Term 1	Term 2
100	393.27	1877	1.16E+06	1.50E+04	2.35E+05	3.77E+04	2.72E+11
250	157.07	7260	4.62E+05	6.76E+06	2.11E+08	6.55E+07	9.75E+13
300	78.33	3629	2.31E+05	2.40E+07	9.06E+08	1.17E+08	2.09E+14
350	0.07	18.74	1.19E+03	6.83E+07	3.06E+09	1.71E+06	3.64E+12

Table 4. 9 The calculated sources of AFD value in the CDO low-k ILD interconnect. The reservoir length is 0.05 μm .

Figure 4. 23 AFD contributions by stress divergence and constant 2 with respect to stress temperature (y-axis log-scale). The reservoir length is 0.05 μm .

For the interconnect structures considered in this work, the maximum AFD at point B at stress temperature of 100 $^{\circ}\text{C}$ is observed to be much smaller than the maximum AFD at 250 $^{\circ}\text{C}$ and 300 $^{\circ}\text{C}$ as shown in Figure 4.24. As can be seen from the above discussion, at a low stress temperature, only the thermo-mechanical stress divergence is dominant while the contribution from constant 2 is quite small. With the smaller maximum AFD, the

vacancy accumulation speed is quite small at low temperature, and thus more time is needed to cause interconnect failure.

Figure 4. 24 Maximum AFD value with respect to the reservoir length in interconnect at different stress temperature

For stress temperature in the range of 250 °C ~ 300 °C, the interconnect is subjected to two effects, namely the thermo-mechanical stress divergence and temperature, and thus their maximum AFD is higher and increasing with temperature as observed in Figure 4.24. When temperature goes to 350 °C, the thermo-mechanical stress drops to zero at SFT, which implies zero driving force, and hence the AFD will be depending on the vacancy diffusion speed, thus the maximum AFD decreases as depicted in Figure 4.24. Hou and Tan [63] developed a lifetime model with stress induced void from energy perspective, and they showed that stress induced void lifetime decreases with temperature up to a critical point, beyond which the lifetime increase with increasing temperature [63]. The similarity between their work and the present work is that the driving force is the only thermo-mechanical stress as no current is flowing in the reservoir region.

Figure 4. 25 The variability chart for MTF proportionality constant at different reservoir length within stress temperature

Figure 4.25 shows the the value of the distance/AFD_{max} which is proportional to the MTF of an interconnect as we have established earlier. Here we only consider Term 2 impact which is dominant the total AFD value. Hence, the lifetime for the interconnect can be expressed as below.

$$MTF \propto \frac{L_{AB}}{\frac{N\Omega D_0}{k_B T} \exp\left(-\frac{E_a}{k_B T}\right) \times \nabla \cdot (\nabla \sigma_H)} \quad (4.7)$$

As N , Ω and k_B are constant, Equation (4.7) can be re-written as Equation (4.8)

$$MTF \propto \frac{L_{AB} \times T \times \exp\left(\frac{E_a}{k_B T}\right)}{\nabla \cdot (\nabla \sigma_H)} \quad (4.8)$$

From the Equation (4.8), we can see that the lifetime is proportional to a temperature function while is inverse with thermo-mechanical stress divergence. Using the value of the distance/ $AFD_{\max}$ at 0.03 μm reservoir length as reference to normalize the value at other reservoir lengths for a given stress temperature, we can derive from Equation (4.8) the reservoir enhancement factor M for a given temperature given as

$$M \propto \frac{L_{AB}(\text{reservoir})}{\nabla \cdot (\nabla \sigma_H(\text{reservoir}))} \times \frac{\nabla \cdot (\nabla \sigma_H(\text{reservoir}=0.03))}{L_{AB}(\text{reservoir}=0.03)} \quad (4.9)$$

Figure 4.26 shows the enhancement factor M for the wide metal line at different stress temperature. The critical reservoir length is observed to be 0.05 μm for all the stress temperature, even though they have different enhancement efficiency. At the stress temperature of 250 $^{\circ}\text{C}$, the enhancement factor is found to be the largest compared with other conditions due to the effect of the high thermo-mechanical stress divergence and vacancy diffusion speed. On the other hand, the enhancement factors show comparable at the rest of stress temperature. The different enhancement efficiency will be further discussed.

Figure 4. 26 Reservoir efficiency at different stress temperature

As observed from Equation (4.9), the enhancement factor is related to AB length as well as thermo-mechanical stress divergence. However, to compare the effectiveness of reservoir effect among different stress temperature, the AB length is considered to be constant since FEA is carried out in the same interconnect. Hence, we only summary the temperature impact on the thermo-mechanical stress, thermo-mechanical stress gradient and thermo-mechanical stress divergence from Table 4.10 to Table 4.13. We also recall the Table 4.7 as discussed in the low-k material impact that thermo-mechanical stress divergence is distributed differently as shown in Table 4.10 in various reservoir lengths.

Reservoir Length	Stress	Stress Gradient	Stress Divergence
0.03	77.54	3542	3.02E+05
0.05	78.33	3620	2.54E+05
0.08	77.58	3617	2.61E+05

Table 4. 10 The simulated maximum stress, stress gradient and stress divergence near point B in the CDO low-k ILD interconnect at stress temperature 300 °C.

Reservoir Length	Stress	Stress Gradient	Stress Divergence
0.03	155.49	7102	6.06E+05
0.05	157.07	7260	4.62E+05
0.08	155.56	7253	5.23E+05

Table 4. 11 The simulated maximum stress, stress gradient and stress divergence near point B in the CDO low-k ILD interconnect at stress temperature 250 °C.

Also, in the same way, Table 4.11 shows the maximum thermo-mechanical stress, stress gradient and stress divergence at stress temperature 250 °C. Since thermo-mechanical stress is also a function with temperature, different reservoir efficiency will be resulted. In the case of stress temperature 250 °C, the thermo-mechanical stress divergence difference between 0.03 μm and 0.05 μm is slightly larger than that of 300 °C. Because lifetime is inversely proportional to the maximum AFD value, in particular, the lifetime enhancement at reservoir length of 0.05 μm over 0.03 μm is the ratio of the stress divergence at reservoir length of 0.03 μm over 0.05 μm, that is $3.02/2.54 (= 1.19)$ at 300°C and $6.06/4.62 (= 1.31)$ at 250 °C. This implies that the lifetime enhancement efficiency at 250 °C as reservoir length increase from 0.03μm to 0.05μm is larger than that at 300 °C, and the ratio of this increase is $1.31/1.19 = 1.1$. Hence, the enhancement factor at stress temperature 250 °C is around 1.1 times larger than that of 300 °C.

Reservoir Length	Stress	Stress Gradient	Stress Divergence
0.03	389.33	17783	1.52E+07
0.05	393.277	18177	1.28E+07
0.08	389.51	18161	1.31E+07

Table 4. 12 The simulated maximum stress, stress gradient and stress divergence near point B in the CDO low-k ILD interconnect at stress temperature 100 °C.

Reservoir Length	Stress	Stress Gradient	Stress Divergence
0.03	-0.403	18.376	1566
0.05	-0.406	18.736	1313
0.08	-0.401	18.693	1344

Table 4. 13 The simulated maximum stress, stress gradient and stress divergence near point B in the CDO low-k ILD interconnect at stress temperature 350 °C.

At the same time, Table 4.12 and Table 4.13 show the impact on the thermo-mechanical stress, thermo-mechanical stress gradient and thermo-mechanical stress divergence at stress temperature of 100 °C and 350 °C. Although the thermo-mechanical stress divergence at stress temperature of 100 °C is around 4 orders higher than that of 350 °C, the enhancement efficiency is comparable. The lifetime enhancement at 0.05 μm over the lifetime at 0.03 μm is 1.52/1.28 (= 1.187) at 100 °C and that at 350 °C is 1566/1313 (= 1.19). That is the reason why the enhancement efficiency is comparable at 100 °C and 350 °C. Hence, we conclude that the lifetime enhancement difference depends on test temperature which will subsequently induce thermo-mechanical stress divergence difference.

4.4 Summary

Finite element analysis with ANSYS software is employed for the present EM models to investigate the mechanism of the effectiveness of the reservoir effect. We illustrate the current density, thermo-mechanical stress, as well as the atomic flux divergence at any nodes of the model, and hence different EM enhancement efficiency can be identified. The effective reservoir volume concept is proved to be insufficient to explain the experimental results because the supply of atoms will not be limited by the effective reservoir volume in the wide metal line where the reservoir length is much smaller than the distance between the via corner and the edge of interconnect line.

From the maximum atomic flux divergence concept approach, we identify that the distance from the maximum AFD location to via corner has significant effect on the EM lifetime in the Cu interconnect. The larger reservoir enhancement rate in the narrow metal is because the maximum AFD sites decrease from two to one as reservoir length increases, and thus the void growth rate decreases. For the case of the wide metal line, the reservoir length is much smaller than the distance from via to metal edge in the width direction, and then the length of AB increases slowly with the increase in the reservoir length. This is the reason why smaller effect of the reservoir length in enhancing EM lifetime for wide metal line as observed experimentally

Simulations are also carried out to investigate the low-k materials impact on reservoir effect. It is found that SiLK low-k interconnect with larger CTE has shorter MTF than the other low-k interconnect. The saturation trend of EM enhancement due to reservoir length is observed for different low-k ILD interconnects. Besides, current density variation is found to be not important for EM improvement, while stress temperature can highly impact the interconnect lifetime and thus the enhancement factor. The temperature and thermo-mechanical stress divergence are discussed to be the dominant factors to influence EM lifetime. The reservoir efficiency is found to depend on test temperature. This different temperature will subsequently induce thermo-mechanical stress divergence difference and thus it causes different reservoir efficiency.

Chapter Five

Conclusion and Recommendations

5.1 Conclusion

EM is a serious reliability issue with rapid shrinkage of interconnects and introduction of low-k materials in Cu metallization. In this work, reservoir effect of EM reliability has been investigated in Cu/low-k dual-damascene interconnects with varied reservoir lengths in both narrow and wide metal lines. Moreover, finite element analysis is also applied to study the mechanism of reservoir effect.

Inline electrical measurement and defect capture confirm the good quality of wafer. Failure analysis revealed that the void formation is always located in the reservoir region. The wide metal has longer MTF as compared with the narrow metal since a larger void size is needed to cause metal trench failure in the wide metal.

MTF is improved as the reservoir length increases from 0 μm to 0.05 μm , and further increases in the reservoir length beyond 0.05 μm do not result in any additional improvement for both narrow and wide metal lines. A critical reservoir length of 0.05 μm is present in the experiment. It is also interesting to note that the maximum MTF enhancement factor is 1.72 in the narrow line, whilst it is only 1.28 times for the wide metal, indicative better effectiveness of reservoir effect on EM for the narrow metal line.

However, the improvement in t_{50} due to reservoir length for the wide metal line does not occur until the length is $0.03\mu\text{m}$ as observed in our experiments.

Finite element analysis with ANSYS software is applied to investigate the mechanism of the effectiveness of the reservoir effect in improving EM reliability as a function of line width. The effective reservoir volume concept is proved to be insufficient to explain the experiment results because the supply of atoms will not be limited by the effective reservoir volume in the wide metal line.

From the maximum atomic flux divergence concept, we identify that the distance from the maximum AFD location to via corner has significant effect on the EM lifetime in the Cu interconnect. The larger reservoir enhancement rate in the narrow metal is because the maximum AFD sites decrease from two to one as reservoir length increases, and thus the void growth rate decreases. For the case of the wide metal line, the length of AB increases slowly with the increase in the reservoir length. This is the reason why smaller effect of the reservoir length in enhancing EM lifetime for wide metal line as observed experimentally.

From the maximum AFD concept, it is found that SiLK low-k interconnect with larger CTE has shorter MTF than the other low-k interconnects because of larger CTE mismatch that causes a large AFD. The saturation trend of EM enhancement due to reservoir length is also observed for different low-k ILD interconnects. Besides, current density variation is found to be not important for EM improvement, while stress temperature can highly impact the interconnect lifetime and thus the enhancement factor.

The temperature and thermo-mechanical stress divergence are discussed to be the dominant factors to influence EM lifetime.

5.2 Recommendations for future research

The main aim of this work was to carry out study on reservoir effect of EM. Through the experiment and simulation, we have developed an explanation in good agreement on effectiveness in reservoir effect in improving EM. Although these major objectives had been successfully achieved, further improvements can be made in the following areas:

1. The finite element analysis in this work is static modeling so that it does not consider the stress relaxation during EM mass transport. However, in reality, the void growth will result in AFD change. Hence, dynamic modeling with void evolution process under the influence of driving force is more appropriate to predict actual failure time at interconnects with different reservoir length. With that model, the dynamic void evolution process could be easily explained.
2. Although simulation is performed at various low-k dielectric interconnects at different reservoir length in this work and it is found that low-k material variation does not change the phenomenon of the lifetime enhancement and saturation with respect to reservoir length, it still lacks of confirmation from experiment. Hence, it is suggested that experiment can be carried out on EM test structures fabricated with different ILD low-k materials to study the reservoir effectiveness.

3. Different current density and temperature impact on the reservoir effectiveness are also studied in this work and it is found that stress temperature can influence the reservoir enhancement factor. Experiment at different stress conditions is suggested to verify the validity of the simulation.

List of Publication

C. M. Fu, C. M. Tan, S. H. Wu and H. B. Yao, “Width Dependence of the Effectiveness of Reservoir Length in Improving Electromigration for Cu/Low-k Interconnects”, *Microelectronics Reliability*, vol.50, no.9-11, pp.1332-1335, 2010

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