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# Effects of Cu-Wire Surface Fluctuations on Early Failures*

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**Abstract:** Different chemical mechanical polishing (CMP) slurries are used to obtain single-damascene Cu-wires with different surface fluctuations as well as pre-existing surface-defects in wires with rougher surfaces. The presence of such pre-existing defects strongly increases the rate of early failures to almost 100%, reduces electromigration lifetime rapidly to the level of early failures, and changes the multimodal failure distribution into monomodal. The activation energy (0.74±0.02eV) for the failure mechanism associated with these pre-existing defects confirms a dominant surface diffusion. It shows how a weakest link approximation analysis can be applied to a single wire by dividing the wire into relevant segments and assigning different failure mechanisms to the various segments. The analysis confirms that, although surface-defects are not the fastest early failure mechanism, the ten times higher surface-defect-density in the rougher wires is responsible for the observed high early-failure rate and unreliable performance.

**Key words:** early failure; surface-defect; weakest link approximation
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## 1 Introduction

Bimodal or multimodal behavior of time-to-failure distributions is frequently observed in electromigration (EM) tests. Early (or extrinsic) failures occur before the anticipated lifetime from a monomodal distribution. This reduces Cu EM lifetimes to an Al(Cu) level or even lower[1,2]. Studies of Al interconnects[3,4] have shown that the presence of pre-existing defects appreciably increases the rate of early failures, and these defect-related early failures can be considerably reduced by increasing the grain size. For Cu interconnects, with their dominant atomic diffusion path along the Cu/dielectric surface rather than along the grain boundaries[5~7], the influence of defects on early failures is expected to be different. The step from CMP to planarize the surface of Damascene lines inevitably results in a surface fluctuation with a certain surface-defect-density. Beside the standard CMP slurry, a dedicated CMP slurry was chosen in this paper, in order to obtain randomly distributed pre-existing surface-defects in combination with a large surface fluctuation. Accelerated EM testing and weakest link approximation (WLA) analysis are applied to investigate the influence of such surface fluctuation/defects on early failure behavior of Cu single-damascene (SD) wires.

## 2 Experiment and results

The SD Cu test lines (0.25μm-wide and 2mm-long) were produced in 600nm-deep oxide trenches; 10nm TaN/15nm Ta was used as barrier

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material with 100nm Cu-seed deposited without vacuum break, followed by electroplated Cu to fill the trenches. For the CMP step, different Cu slurries were applied to two sets of samples (Set_A and Set_B): slurry A with pH ≈ 7.5, containing abrasive alumina particles, versus the more acidic slurry B (pH ≈ 2.5), with abrasive silica particles; each set had 16 samples. Typical top-down scanning electronic microscope (SEM) images after the CMP are presented in Fig. 1. At a given resolution, the surface of Set_A is smooth, and defects can occasionally be observed. The second slurry (set_B) results in a rougher Cu surface with far more pit-like defects. Most of the pre-existing surface-defects are elliptical and distributed randomly along the length of the Cu line; their dimensions vary from 20 to 200nm. After CMP, the samples received a 50nm SiC top hardmask and were further protected from corrosion by a 330nm/500nm thick $SiO_2$/SiN passivation layer. The average resistance increases from 250Ω (Set_A) to 300Ω (Set_B), indicating an effective cross-section reduction of about 17% due to the larger surface fluctuation/defect-density. After measuring and packaging (ceramic package, Al-Si wire), the samples were tested at 300 ℃ and 3MA/cm$^2$ in an Aetrium 1164 EM test system. A 20% resistance increase is used as a failure criterion. The experiment was terminated after 1027 test hours.

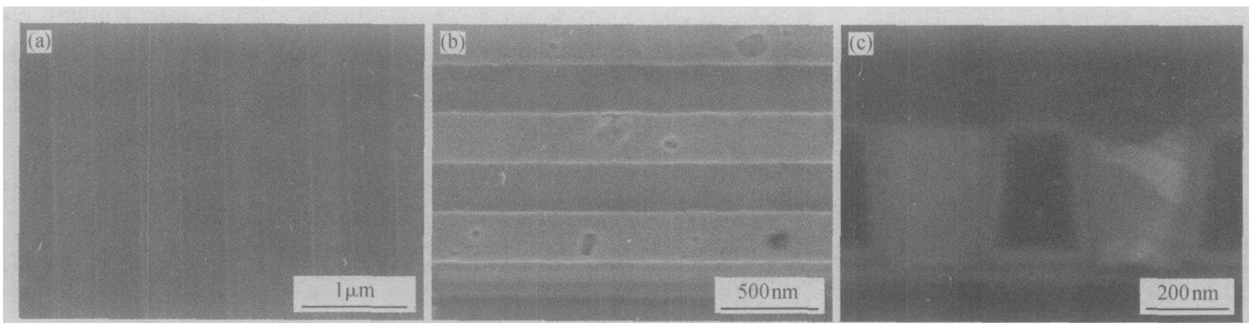


Fig. 1 SEM pictures of two different sets of samples without (a) and with (b, c) pre-existing surface-defects

The cumulative failure distributions (CFD) for samples at the above-mentioned stressing conditions are shown in Fig. 2 (symbols). A multimodal CFD is evident for Cu-wires with negligible surface fluctuation (Set_A). Early failures occurred within 400h at a rate of 50% (8 out of 16 samples in Set_A). The intrinsic EM-induced failure triggered after 1002h, and more than 40% (7 out of 16) samples still survived after 1027h (empty circles in Fig. 2), so the median lifetime ($t_{50}$) of the intrinsic failure distribution is expected to be longer than 1000h. Furthermore, the extrinsic failure distribution itself is far from monomodal. This implies the coexistence of several different early failure mechanisms in these SD Cu-wires, assuming the failure distribution due to a given kind of defect is approximately lognormal[8]:

$$f(t) = \frac{\exp[-(\ln t)^2/2\sigma^2]}{x\sigma\sqrt{2\pi}} \tag{1}$$

where $\sigma$ is the shape parameter.

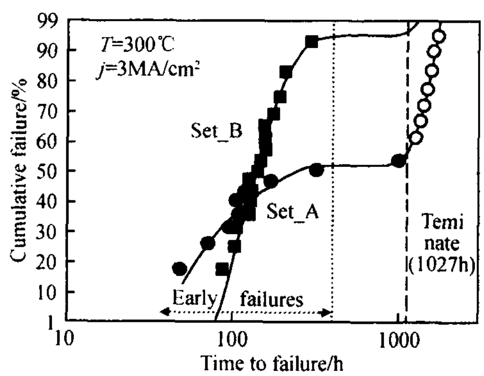


Fig. 2 Time to cumulative failure distributions of samples without (Set_A) and with (Set_B) pre-existing surface-defects Symbols are experiment results, and curves are simulated. Empty circles are surviving samples after 1027h.

The CFD of the Cu-wires with pre-existing surface-defects (Set _ B) is almost monomodal except for a small tail at the right edge. These samples yield a $t_{50}$ of only 145h with shape parameter $\sigma = 0.24$. All the failure times in Set _ B fall into the time scope of early failures defined in Set _ A, indicating the rate of early failures to be strongly increased to nearly 100 %, and EM lifetimes to be reduced to the level of early failures. It is interesting to note that before the surface-defect-related failures are triggered in Set _ B (at about 90h), already more than 10 % of the samples from Set _ A have failed. Clearly another fast failure mechanism with an even smaller $t_{50}$ is present in Set _ A. In subsequent testing we have unsuccessfully tried to replicate this fast failure mechanism. We therefore consider it to be rare and entirely processing-related.

The CFDs of Set _ B under different temperature stress are shown in Fig. 3. Maximum-likelihood-estimate-based analysis suggests an activation energy of about 0.74eV for the related failure mechanism. This would conform to typical activation energies for Cu diffusion along the top surface. FIB analysis on postmortem samples in Set _ B (see e.g. Fig. 4) suggests that the density and size of surface-defects increase under stress due to EM-induced surface diffusion in Cu. This results in a slowly increasing Cu-wire resistance followed by a sudden and catastrophic surface-defect growth.

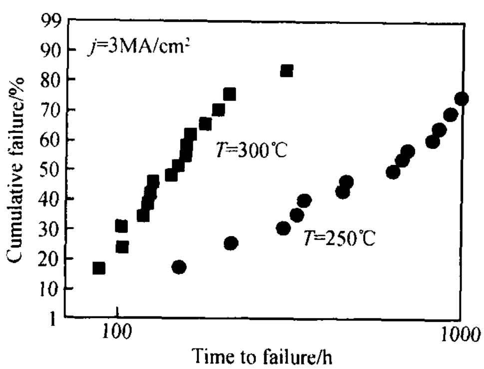


Fig. 3 Time to cumulative failure distributions of samples with pre-existing surface-defects (Set _ B) under different temperature stress The activation energy is around 0.74 ±0.02eV.

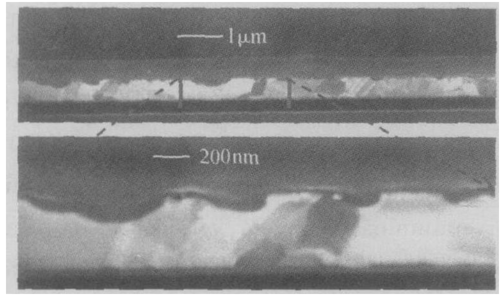


Fig. 4 Postmortem FIB analysis of samples with pre-existing surface-defects (Set _ B)

## 3 Analysis and discussion

The weakest link approximation[9] is used to analyze the above-presented experimental results. According to the WLA, the Cu-wire can be treated as a serial chain of statistically independent elements (Cu segments), which fails whenever any one of the individual elements fails. In this view, elements with pre-existing defects are considered weak links, prone to fail sooner than others. Therefore the CFD of the whole structure is given by the minimum order statistic of the CFD of the individual elements[3,9,10]:

$$F(t) = 1 - \prod_{i=1}^{n} [1 - F_i(t)] \qquad (2)$$

where $F(t)$ and $F_i(t)$ are the probabilities of the whole wire and the $i$-th element, respectively, failing by time $t$, and $n = L/l_E$ is the number of elements, where $L$ and $l_E$ are the wire and element lengths. Furthermore, if the $i$-th element is subjected to two statistically independent failure modes, its CFD is a mixture of the CFDs of these failure modes[10]:

$$F_i(t) = pF^D(t) + (1 - p)F^I(t) \qquad (3)$$

where $F^D(t)$ and $F^I(t)$ are the distributions of defect-related and intrinsic EM-induced failure in this element, respectively, and $p$ is the probability of defect-related element failures.

Because of the short length effect in Cu interconnects, the threshold product at 300 ℃ lies in the range of 2800 to 3500A/cm for SD Cu[11]. So $l_E$ should be much longer than 10μm at the given test conditions (300 ℃ and 3MA/cm$^2$). In this case, the 2mm-long Cu-wire is divided into 12 elements. The length of each element is 167μm, long enough to avoid any short length effect. Three failure mechanisms are considered: an intrinsic EM-induced one in the absence of defects, a surface-defect-related one, and a fast failure mechanism.

According to the different failure mechanisms, the 12 elements are grouped into three types, the diagrams of which are inserted in Fig. 5. There are no defects in element Type_Ⅰ, and only the intrinsic EM-induced failure mechanism is present. Elements Type_Ⅱ and Type_Ⅲ are respectively subjected to the surface-defect-related failure mechanism and the rare processing-induced failure mechanism.

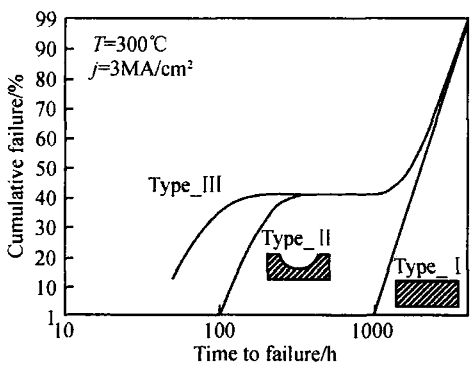


Fig. 5 Simulated time to cumulative failure distributions of different element types Inserts: diagrams of different types of elements

Figure 5 represents the simulated CFDs for different element types estimated by Eq. (2). The $t_{50}$ and $\sigma$ of each mechanism for a WLA element (167μm-long Cu segment) are shown in Table 1, with test conditions of 300 ℃ and 3MA/cm$^2$. It is typically assumed in this type of simulation that the presence of initial defects accounts for 33 % of the failures.

Using the CFDs of the single elements, the CFD of the whole wire is calculated by Eq. (3). The differences between the two sample sets can be simplified as follows: Set_B has a higher surface-defect-density, while Set_A has three failure mechanisms. In our WLA model, the samples in Set_A are treated as a chain of 10 Type_Ⅰ elements, 1 Type_Ⅱ element, and 1 Type_Ⅲ element. The chain of Set_B contains 2 Type_Ⅰ elements and 10 Type_Ⅱ elements. In fact, here we assume that the surface-defect-density in Set_B is ten times higher than in Set_A. The simulation results shown in Fig. 2 (curves) fit the experiments quite well, indicating a ten-fold surface-defect-density increase in the samples with pronounced surface roughness and resulting in a pronounced early failure rate and reduction of $t_{50}$.

Table 1 Parameters of different failure mechanisms and their relative weight in different element types

| Mechanism | | Fast | Surface-defect | Intrinsic |
|---|---|---|---|---|
| $t_{50}$/h | | 80 | 180 | 2100 |
| $\sigma$ | | 0.4 | 0.3 | 0.3 |
| Weight | Type_Ⅰ | | | 100 % |
| | Type_Ⅱ | | 33 % | 67 % |
| | Type_Ⅲ | 33 % | | 67 % |

Further experiments are ongoing to assess how various slurry components and the quality of the Cu surface are interrelated. A more comprehensive analysis, taking into account these interdependencies as well as the effect of CMP-induced corrosion, is in preparation.

## 4 Summary

Different CMP slurries have been used to obtain single-damascene Cu-wires with varying surface fluctuations and pre-existing surface- defects. The presence of such pre-existing defects strongly increases the rate of early failures almost to 100 %, reduces electromigration lifetime rapidly to a level of early failures, and changes the multimodal failure distribution to monomodal. It corresponds to a surface-driven failure mechanism with activation energy of 0. 74eV. A weakest link approximation analysis of the failure times from these Cu-wires was performed, indicating a ten-fold increase in surface-defect-density and a corresponding overall high early failure rate and poor EM performance.

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# Cu导线表面起伏度对其早期失效的影响*


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**摘要**: 不同化学机械抛光剂使单层大马士革Cu导线表面起伏程度不同. 扫描电镜观察到明显的缺陷出现在大起伏的Cu导线表面. 这种表面缺陷导致早期失效比率剧增至几乎100%,电迁移寿命猛降至早期失效的量级,失效时间分布从多模变为单模. 其相应的失效机制激活能为0.74±0.02eV,说明失效主要是由Cu原子沿导线表面扩散引起的. 最弱链接近似被用来分析单根Cu导线:Cu导线被适当均分为若干相互串联、失效机制不同的Cu块,任何一个Cu块的失效都会使整根Cu导线失效. 分析结果表明,虽然表面缺陷不是最快的失效机制,但大起伏Cu导线的表面缺陷密度是另一种的10倍以上,这是其早期失效比率高和可靠性较低的主要原因.



**关键词**: 早期失效; 表面缺陷; 最弱链接近似

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