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Mechanism investigation of pre-existing void-induced multi-modal electro-migration behavior

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Abstract: A multi-modal time-to-failure distribution for an electro-migration (EM) structure has been observed and studied from long duration *in-situ* EM experiment, for which the failure mechanism has been investigated and discussed comprehensively. The mixed EM failure behavior strongly suggest that the fatal voids induced EM failure appear at various locations along the EM structure. This phenomenon is believed to be highly related to the existence of pre-existing voids before EM stress. Meanwhile, the number and location of the pre-existing voids can influence the EM failure mode significantly. Based on our research, a potential direction to improve the EM lifetime of Cu interconnect is presented.

Key words: reliability; electro-migration; multi-modal; pre-existing void

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1. Introduction

As a major reliability concern for Cu interconnects, electro-migration (EM) is highly related to the process capability in back-end-of-line (BEOL) of wafer fabrication. For years of investigation, EM persists as a mass transport phenomenon in which the diffusion of atom is activated by transfer of momentum from electron wind in the presence of an electric field[1]. As a result, an atomic flux divergence can be induced along the interconnect. At sites where there is a net depletion of atoms, EM occurs so that local stresses become increasingly tensile, which can eventually lead to voiding in the interconnect once a critical tensile stress value is reached, which can subsequently lead to an EM failure[2]. As VLSI continues to scale down and plenty of new materials and process have been introduced, EM reliability challenge in terms of higher current density application is a potential trade-off, an effective way to improve Cu interconnect EM performance, which is always a need.

In EM reliability estimation, an ideal situation is that failure occurred in the same mode for all units, which means the failure mechanisms are accordant. Correspondingly, the time to failure (TTF) distributions can be expected to be uniform so that a small lognormal sigma can be expected, which is beneficial for the EM lifetime extrapolation. For that which is commonly used via above Cu interconnect structure, it have been widely revealed that the EM failure most likely occurs at the base of via near the end of cathode as it suffers the maximum EM flux divergence[3]. However, it often appears in in-situ EM experiments that voids can be observed at various locations that do have a distance away from the cathode in the same group of samples[3], it indicates that failure mechanism among them may differ. When mixed failure mechanisms exists, failure can be dominated by void nucleation (t_{50}/j^2) or void-growth (t_{50}/j)[4]. As a result, EM TTF data often show a complex behavior, so called bi-modal or even multi-modal, suggestive of the existence of multiple failure modes[1, 5, 6].

A number of investigations have been carried out to clarify the origin of these voids found at a distance away from the cathode. It has been revealed that the voids can be due to EM flux divergence associated at grain boundaries, or are pre-existing. In Cu metallization, the Cu/dielectric cap interface is the fastest diffusion path instead of grain boundaries[7–9]. Thus, void formation due to a flux divergence at the cap/grain boundaries junction at a distance away from the cathode requires a large difference in diffusivity value between the adjacent grains, or having a long cluster of high-diffusivity grains, which both are very unlikely in Cu metallization[10]. Choi *et al.* reported that the observation of voids at locations other than the end of cathode is highly related to the growth of the pre-existing voids instead of the nucleation of new voids by means of numerical simulation[11]. Moreover, when pre-existing voids are within a current-density-dependent critical length from the cathode, it is difficult for new voids nucleation at the cathode and EM failure occurs only when the pre-existing voids grow to a critical size[12]. However, so far there is still a lack of visible evidence that can confirm the relationship between the voids observed away from cathode and pre-existing voids.

In this paper, we report a series of new observations from in-situ EM experiment, in which a number of situations that voids found at various locations in the studied EM structure are involved. Based on which, the failure mechanism of each mode as well as the relationship between pre-existing voids and multi-modal EM TTF distribution is discussed in detail.

2. Experiment

A commonly used upstream via-terminated Cu interconnect test structure was fabricated with 55 nm Cu/low-*k* technology. The experiment is focus on the layer of upstream metal 2 (M2), which means that the current stress is forced from met-

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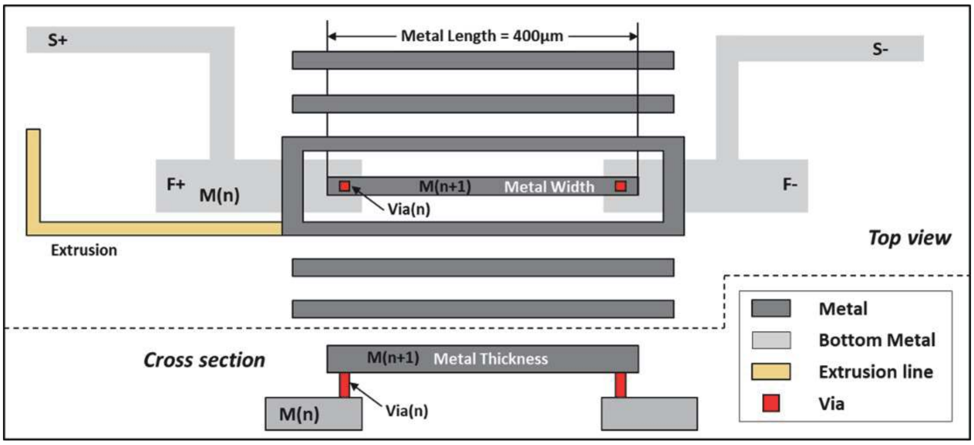

Fig. 1. (Color online) Schematic diagram of EM structure.

al 1 (M1) to and throughout the test line in M2, and back to M1. The length and width of test metal line are 400 μm and 90 nm, respectively. Surrounding the test line are extrusion line and several dummy lines acting as supporting material in CMP process. The low-*k* dielectric material was SiCOH-based. The Ta/TaN liner was deposited before damascene Cu was formed as barrier layer. The top surfaces of the metal were finally passivated with SiCN. Fig. 1 shows the cross-sectional schematic diagram of the test structure.

The accelerating EM test was employed in Qualitau test system. A current density of 1 MA/cm^2 was stressed on all the test samples at a temperature of 325 ˚C. The samples' resistances were monitored by the Kelvin method during the whole EM stressed period and a 10% resistance increase was regarded as the failure criteria. To orient the site of the void nucleation and growth, the microstructures of the tested samples were investigated by scanning electron microscopy (SEM) and the focused ion beam (FIB) and transmission electron microscopy (TEM) equipment. In order to confirm the absence of Cu at the location of void observed by SEM or TEM, EDX element mapping analysis was employed.

3. Result and discussion

3.1. Experiment results

To exclude the contingency of the experiment, the results of several times previous EM reliability tests of the studied structure, including the time-to-failure (TTF) distribution and the median time to failures (t_{50}), and the lognormal sigma (σ) of the TTF distribution, are given in Fig. 2. It can be seen that both the TTF distribution and t_{50} of several confirmation EM runs are statistically comparable, which indicates the failure mode is repeatable and stable. The big σ obtained from every test means the TTF uniformity is poor and severe multi failure modals existed. Considering the test time limitation, these experiments were stopped at 1000 au meanwhile failure ratio is higher than 50%.

A new experiment is carried out in order to fully understand the failure behavior of this Cu EM structure, the TTF distribution of Case 5 is plotted in Fig. 3. Three out of total 24 ea still did not fail when the test reaches around 2000 au, a detailed physical failure analysis comparison can be made with other failed samples to clarify the inherent difference.

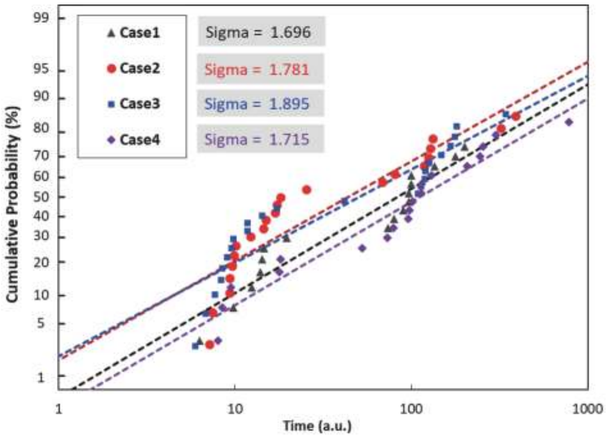

Fig. 2. (Color online) TTF distribution confirmation at several runs.

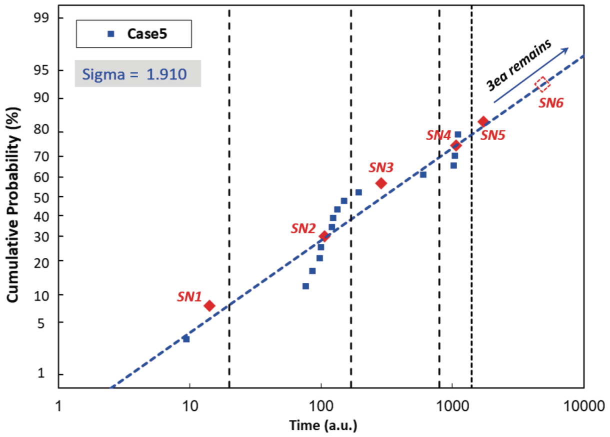

Fig. 3. (Color online) EM TTF distribution at long time intended test.

It clearly shows that the test structure has five types of failure mode at least, which resulting in an extremely poor uniformity of TTF distribution so that a very big σ. Commonly, a big lognormal sigma of the TTF distribution will lead to a short EM lifetime. On the other hand, Fig. 4 shows the relative resistance changes along time of all EM tested samples. Although the failure modes and TTFs vary a lot, all samples exhibit a similar profile of resistance evolution. That is, the resistance remains almost unchanged over a long period of time during the EM stress. Until a critical point that the volume of EM induced void reaches the critical size, the resistance will increase sharply to reach the failure criteria.

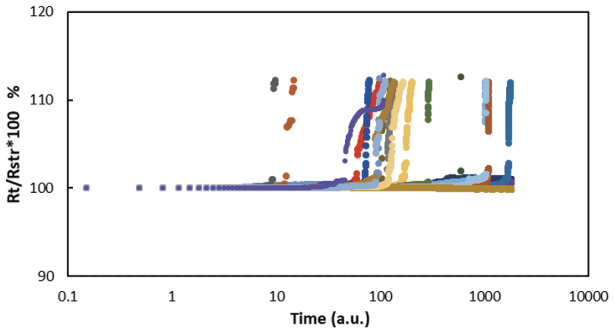

Fig. 4. (Color online) Relative resistance changes over time during EM stress.

Table 1. The initial resistance and TTF of all selected samples.

Sample	R_0 (Ω)	TTF	Sample	R_0 (Ω)	TTF
SN1	761	14	SN4	769	1071
SN2	748	120	SN5	757	1743
SN3	788	289	SN6	786	/

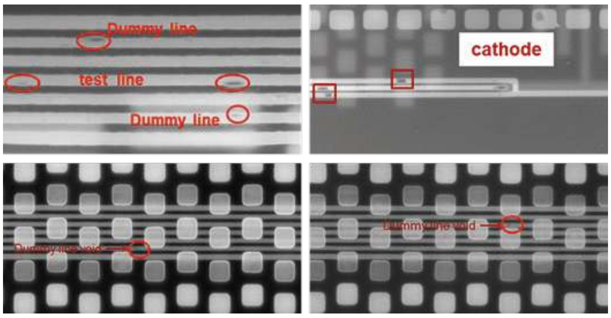

Fig. 5. (Color online) Top view SEM images of selected EM structures.

3.2. Failure mechanism analysis

The samples are grouped according to the failure modes, dividing by the dash line as shown in Fig. 2. A representative sample is selected from each of groups for failure analysis, the definition of selected sample are also marked in Fig. 2 as SN1-6. Table 1 lists the initial resistance and TTF of all selected samples. It can be seen that no obvious difference in initial resistance is found among them, indicating that the initial states of all selected EM samples are consistent.

First of all, we find that all of the selected samples have a common point from the observation of the top view SEM, here are some representative images shown in Fig. 5. It shows that for all selected EM structures, voids, more or less, are randomly distributed along the Cu metals of EM structures. It is believed that these voids pre-existed before EM current stress as they are also widely found at dummy metals, through which there is no current flowing. The severe multi-modal EM behavior that the studied structure exhibits is supposed to be related to these pre-existing voids.

To clarify the failure mechanism in this case comprehensively, a physical failure analysis method including typical top view SEM, cross-sectional TEM, and EDX element mapping is employed for all selected samples. The relative distance from void to cathode, void to anode, void to void (for cases that have multiple voids) are measured and marked at the corresponding images to investigate the influence of pre-existing void to the failure mode of EM structures.

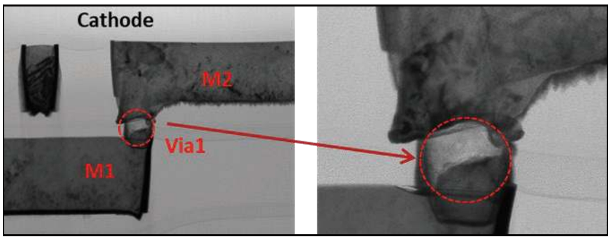

Fig. 6. (Color online) Cross-sectional TEM result of EM structure SN1.

For early fail sample SN1, it is clearly shown that the void is located directly in the cathode via, as seen in Fig. 6. The volume of the void takes the whole cross-sectional area of the cathode via that leads to a jump shift of sample's resistance. In a via-terminated EM structure, the cathode via is often considered as the weakest point of the void nucleation and growth because 1) It suffers the maximum electro-migration flux divergence; 2) It is the starting point of the electron wind, during the process of EM stress. Obviously, an early failure as SN1 likely happens even when a small void nucleate and grows quickly under the cathode via in an upstream EM structures. This phenomenon has also been widely discussed in previous research[2, 13].

As for SN2 and SN3, seen from Figs. 7(a) and 7(b), respectively, the single and fatal void in them have both moved on to the metal line as though still near to cathode via. It is worth noting that with the increase of samples TTF (120 and 601 au for SN2 and SN3, respectively), the failure position is farther away from the cathode via (2.1 and 6 μm for SN2 and SN3, respectively). It can be interpreted that for the metal line of an EM structure, the closer position to the end of the cathode via the higher electro-migration flux divergence suffers and the easier void nucleation occurs.

While for SN4, although it is still close to cathode relative to anode, a single and fatal void is found about 29 μm away from the cathode, as shown in Fig. 8. Correspondingly, its TTF is more than 1000 au when failure happened, and we believe it could be attributed to the tensile stress decreases with the distance away from the cathode. However, considering that the fatal void has been so far away from the end of cathode, it is speculated that this void does not nucleate and grow at the observed position under EM stress, but it grew from a pre-existing void. Firstly, when a void is pre-existing, the stress around the void, within a critical length, will be relaxed. Thus the void nucleation between this pre-existing void and the end of cathode will be restrained. Therefore, the pre-existing void which under EM stress will grow in place or de-pin from grain boundaries and drift towards the cathode then coalesce with other voids[13]. Moreover, as the pre-existing void is continuous to grow due to the electron wind force, the place closer to cathode always experiences a zero net atomic flux so that the void nucleation will not occur. Eventually, failure in an EM test with pre-existing void in line can occur only when this void grows to a critical size and a very long TTF obtained when the void position is far away from the cathode.

It clearly shows that, from the comparison of failure analysis results among SN2-4, a multi-modal TTF distribution can be easily resulted by the single and fatal void forms at different places for different group of samples, although the failure site near the cathode terminal is still observed.

With regard to SN5 which experiences the longest TTF

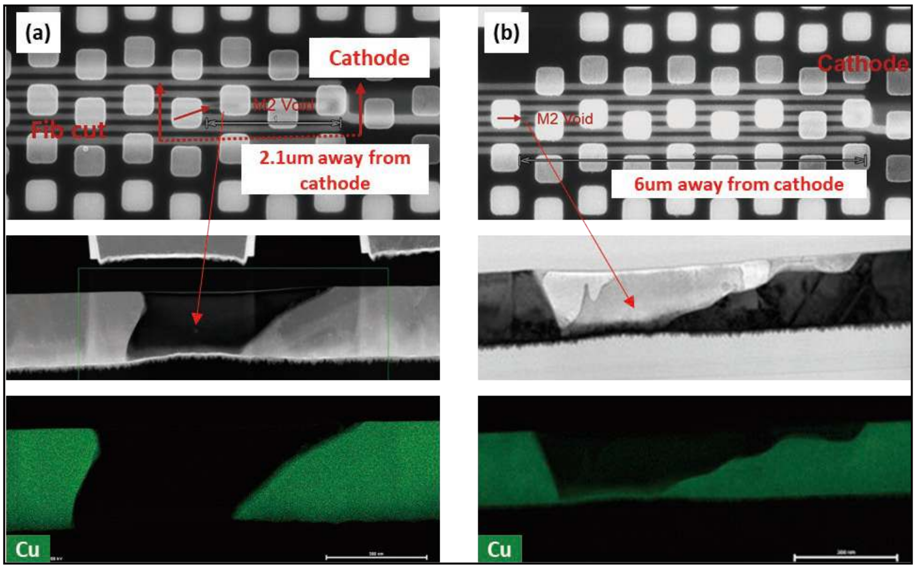

Fig. 7. (Color online) Top view SEM, side view TEM results and EDX element mapping results of EM structure. (a) SN2. (b) SN3.

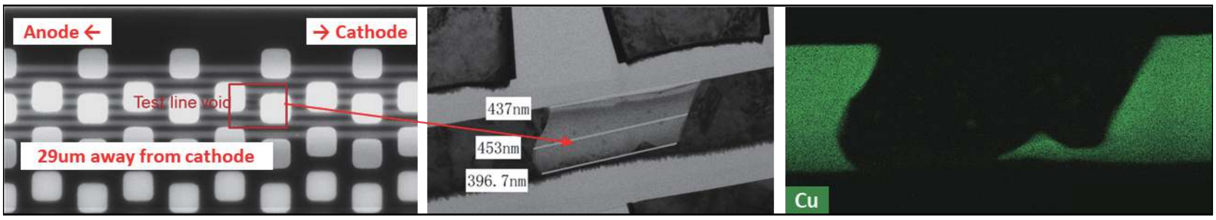

Fig. 8. (Color online) Top view SEM, side view TEM results and EDX element mapping results of EM structure SN4.

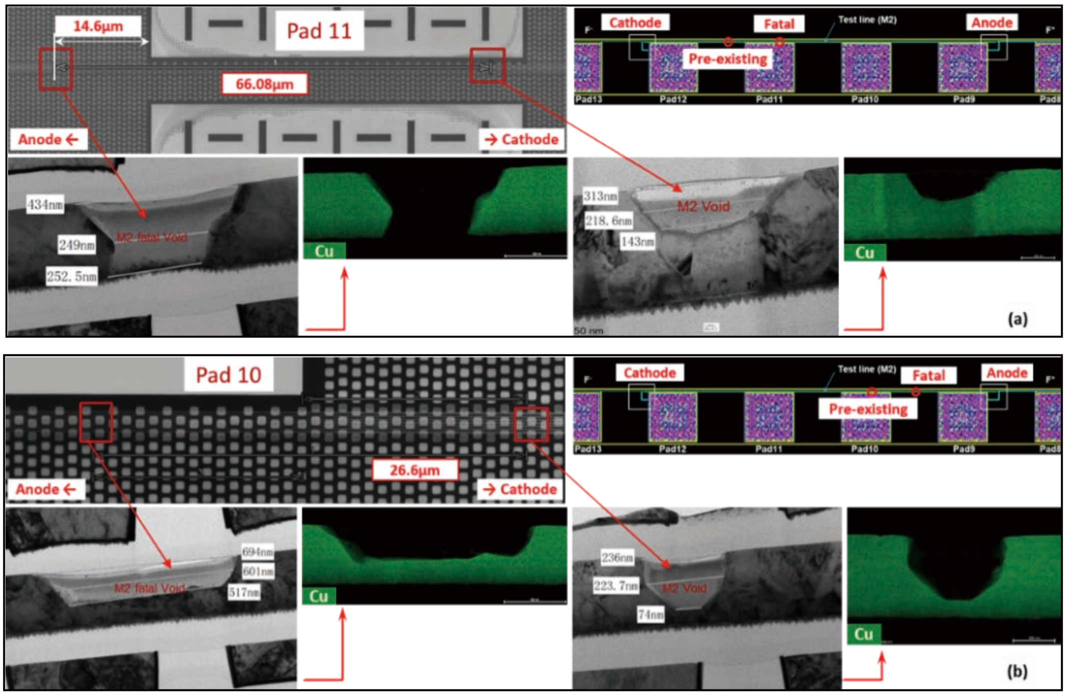

Fig. 9. (Color online) Top view SEM, side view TEM results and EDX element mapping results of EM structure. (a) SN5. (b) SN6.

(1743 au) among all of failure samples as well as SN6 that had not failed yet until the experiment is stopped intentionally, by which the experiment duration had been over 1800 au. In both cases, two obvious voids in metal line are found far away from the end of cathode, but the failure sites in each case are different, as seen in Figs. 9(a) and 9(b), respectively. Firstly, in the case of SN5, the two voids are both too far away from cathode, beyond 100 μm, to be EM induced due to the reasons mentioned before. As a result, the EM stress tends not to induce a new void nucleation at other place due to the absence of net atomic flux, but make the pre-existing voids grow in original place or drift towards to the cathode.

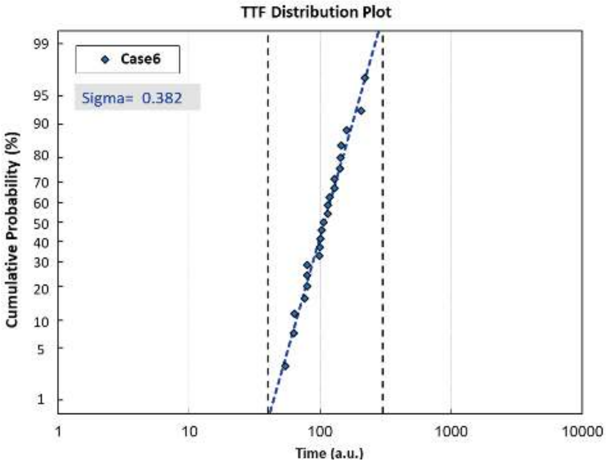

Fig. 10. Time to failure distributions plot for the EM samples with less defeat.

Obviously, it is much more difficult to make a pre-existing void that far away from cathode grow to the critical size because of the tensile stress losses with the increase of the distance from pre-existing void position to cathode terminal. On the other hands, two pre-existing voids themselves will restrain the void growth under EM stress to each other. As a result, an extremely long TTF appeared. Of the two observed voids, the one that takes the whole cross section of metal line is the fatal one, which means it is more sensitive to EM stress.

As to SN6, the failure sites move even farther away from the end of cathode, actually have been closer to anode relatively. In this region of the test metal line, the compressive stress and the metal atom accumulation are dominant. Still, instead of nucleating a new void at other place due to the absence of net atomic flux, the EM failure will be caused by the pre-existing voids grow to the fatal void under the EM stress. Obviously, the failure time will be significantly extended because of the compressive stress and the compensation effect of metal atom accumulation. It can be expected that the fatal void is the longer one in length direction according to the analysis result of SN5. Given that the size of this fatal void just reaches about a half of the cross-sectional area of metal, it may still be a long time before EM failure occurs.

Finally, to study the pre-existing void EM dependence, by controlling and monitoring in-line defect severity, a piece of wafer with less pre-existing voids in metal line is sorted out for the EM performance comparison. The test result is shown in Fig. 10. The conclusion is clear that the TTF data exhibits a more uniform distribution, which means each of tested sample experiences the same failure mechanism. Based on the discussion above, it is believed that the void nucleates and grows to a fatal size near the cathode in this case. It is a strong proof that the observation of voids at locations other than the end of cathode derive from the voids grew from the pre-existing voids. At the same time, it presents a potential direction to improve Cu interconnect EM performance, which is controlling Cu plating well and following processes to minimize the weak points of the pre-existing void formation.

4. Conclusion

A severe multi-modal EM failure behavior and its failure mechanism have been reported and discussed in this paper. With the help of failure analysis technics, it is believable that this phenomenon is attributed to the fatal voids grow or move along the test line at different locations, the intimate relationship of this observation to the existence of pre-existing voids before EM stress is proven. We also demonstrate the number of pre-existing voids and where they located originally can influence the EM failure time greatly, and this is suggested that the pre-existing void along metal test line could be a factor for a bi-modal or even multi-modal EM failure behavior.

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References

[1] Strong A W, Wu E Y, Vollertsen R P, et al. Reliability wearout mechanisms in advanced CMOS technologies. John Wiley & Sons, 2009

[2] Hau-Riege C S. An introduction to Cu electromigration. Microelectron Reliab, 2004, 44(2), 195

[3] Korhonen M A, Bo/rgesen P, Tu K N, et al. Stress evolution due to electromigration in confined metal lines. J Appl Phys, 1993, 73(8), 3790

[4] Meyer M A, Herrmann M, Langer E, et al. In situ SEM observation of electromigration phenomena in fully embedded copper interconnect structures. Microelectron Eng, 2002, 64(1–4), 375

[5] Lloyd J R. Electromigration failure. J Appl Phys, 1991, 69(11), 7601

[6] Filippi R G, Wang P C, Brendler A, et al. The effect of a threshold failure time and bimodal behavior on the electromigration lifetime of copper interconnects. 2009 IEEE International Reliability Physics Symposium, 2009, 444

[7] Hu C K, Harper J M E. Copper interconnections and reliability. Mater Chem Phys, 1998, 52(1), 5

[8] Gan C L, Thompson C V, Pey K L, et al. Effect of current direction on the lifetime of different levels of Cu dual-damascene metallization. Appl Phys Lett, 2001, 79(27), 4592

[9] Dai Y Y, Ng M Z, Anantha P, et al. Enhanced copper micro/nanoparticle mixed paste sintered at low temperature for 3D interconnects. Appl Phys Lett, 2016, 108(26), 263103

[10] Lane M W, Liniger E G, Lloyd J R. Relationship between interfacial adhesion and electromigration in Cu metallization. J Appl Phys, 2003, 93(3), 1417

[11] Rosenberg R, Edelstein D C, Hu C K, et al. Copper metallization for high performance silicon technology. Ann Rev Mater Sci, 2000, 30(1), 229

[12] Mario H, Lim M K, Gan C L. Impact of pre-existing voids on electromigration in copper interconnects. 2012 19th IEEE International Symposium on the Physical and Failure Analysis of Integrated Circuits, 2012, 1

[13] Choi Z S, Lee J, Lim M K, et al. Void dynamics in copper-based interconnects. J Appl Phys, 2011, 110(3), 033505

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