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Electromigration-induced local dewetting in Cu films

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***Abstract*— The continuous downscaling of microelectronics has introduced many reliability issues on interconnect. Electromigration and dewetting are major reliability concerns in high-temperature micro- and nanoscale devices. In this paper, the local dewetting of copper thin film during the electromigration test was first found and investigated. When the high current was applied, the dewetted copper forming around the edge was observed at the cathode of the conductor. Furthermore, the effect of temperature and conductor size on local dewetting was investigated. Our proposed mechanism for local dewetting is in good agreement with experimental findings.**

Keywords—Dewetting, Electromigration, Copper, Thin film

I. INTRODUCTION

The rapid development of the semiconductor industry has driven intensive integrated circuit (IC) design in electronic devices. To realize the complex functions, the tiny chip contains hundreds of billions of transistors. The increasing density of transistors requires the scaling down of device feature size, which induces several reliability issues. The electromigration (EM) effects turned out to be one of the significant issues for copper interconnects [1].

The downscaling of the interconnect is not only in width but also in the thickness of the metal film down up to the nanoscale. At high temperatures, the thermal stability of the thin metal films has also become a reliability concern. Particularly, in high-temperature microelectronic and integrated systems, solid-sate dewetting of thin metal films or interconnects can cause the discontinuity of the metal contact, which can result in device failure [2-6].

During the deposition process of thin metal films, the atomic motion is restricted. Thus equilibrated lattice may not be achieved, and the entire film is in a meta-stable state. When applying external perturbations (e.g., annealing), the original state of the thin film is broken, and surface energy increases, which in turn leads to the disintegration of the film into discrete islands [7-10]. The breaking down of the thin film into isolated islands through agglomeration at elevated temperatures is known as solid-state dewetting. Generally, the external perturbation temperature is much lower than the film melting point and depends on the film thickness and substrate [11].

In this paper, we found the local dewetting phenomenon on copper thin film during the EM test. At the cathode side of the copper stripe, dewetted copper formed around the copper edge and attached on the TiN layer, and this phenomenon was not observed at the anode end. We speculated that this was due to the amount of local Joule heat generated by the interfacial oxide layer under high current density. The experimental results verified our hypothesis.

II. EXPERIMENTAL

A. Sample Fabrication

The sample fabrication begins with growing 300 nm think SiO_2 by thermal oxidation on a 525-µm-thick (100)-oriented 100 mm silicon wafer. Then, a 200 nm thick TiN layer was deposited at 350ºC by reactive magnetron sputtering onto the thermal oxide layer and patterned using lithography and dry etching. Subsequently, a Cu film was sputtered at room temperature on TiN with a base pressure of 10^{-8} Torr using argon gas flow. The deposition rate is 3.76 nm/s under 1000 W applied power.

A lithographic step was followed to form the Blech structure, and the Cu segments are connected by the TiN layer underneath. The wet chemical etching was adopted due to its high selectivity. However, the most widely used etchant, ferric chloride ($FeCl_3$) [12], contains Fe, which could induce the contaminated ions into the sample, affecting the electromigration test. The alternative solution APS-100 (15 – 20 wt.% Ammonium Persulfate; 80 – 85 wt.% Water) shows low uniformity and over-etch behavior. Therefore these two standard solutions could not be used. In our case, we used $Na_2S_2O_8$ (1 wt%)/ H_2SO_4 (0.25 wt%)/ H_2O at 30ºC to obtain the well-defined segment edges. The optimal etching rate was determined by optical microscope inspection, approximately 80 nm/min. After etching, we rinsed samples in the NMP (1-Methyl-2-pyrrolidone) heated at 70 ºC to remove the residual resist. Before the EM test, an extra cleaning step using acetone in an ultrasonic bath was employed to avoid potential ion contamination.

B. Measurement Setup

The accelerated EM test was carried out in a temperature controlled setup that consists of a Nextron high-temperature microprobe station, a vacuum system, a source meter, and a temperature controller. The chamber can be pumped down to 10^{-6} mbar with the assistance of the PFEIFFER vacuum system. The electrical properties of the devices are measured using rhodium-coated needle around the heating stage. The Keithley 2612B source measurement unit (SMU) is used for

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resistance measurement of the test devices. Figure 2.1 shows a schematic overview of the measurement setup.

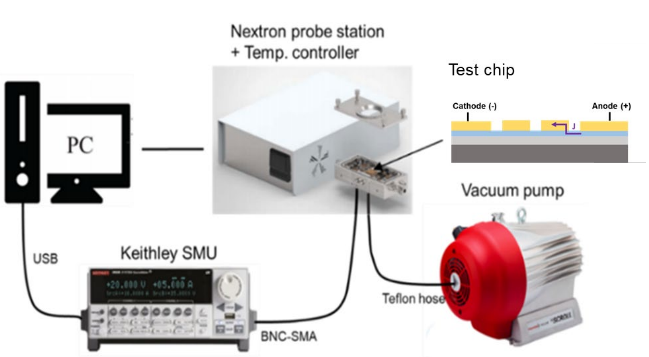

Figure 2.1. The schematic overview of the setup.

III. RESULTS AND DISCUSSION

The micrographs shown in Figure 3.1 clearly reveal that the surface of the copper interconnects have increased roughness when exposed to different heating temperatures in a vacuum. There is no obvious morphological change on the copper surface heated below 450ºC for 3 hours. However, when the heating temperature reaches 550ºC for 1 hour, small voids and several hillocks formation of Cu film can be observed. As the heating temperature rises, well-developed voids appear, and void size increases at 600ºC. At 650ºC, several isolated islands formed, and copper grain size increased. The result implies that the dewetting of 200 nm thick Cu film starts at least 550ºC, and the distribution of Cu islands is homogeneous over the Cu stripe due to the uniform heating temperature throughout the structure.

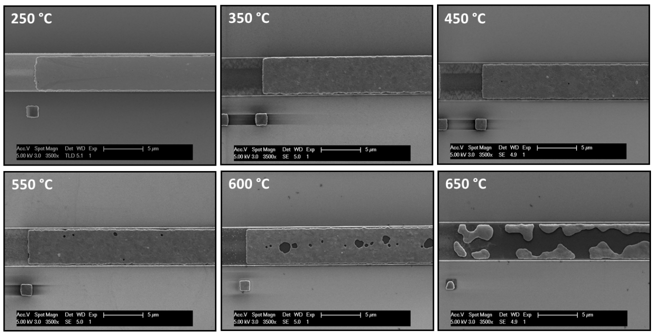

Figure 3.1. SEM micrographs showing morphological change taking place in 200 nm thick Cu film at different heated temperatures for 3 hours (≤450ºC) and 1 hour(≥ 550 ºC).

In the accelerated experiment on EM, dewetting of 200 nm thick copper films occurs at a lower externally applied temperature. Figure 3.2 shows the failure of the Cu stripe under an applied current density of 1 MA/cm^2 at 250ºC for 3 hours. At the cathode of the Cu stripe, significant dewetting of the copper film can be observed with large copper particles formed around the stripe. However, there is no dewetting in the middle of the conductor and near the anode side. At the anode, only the formation of small hillocks can be observed.

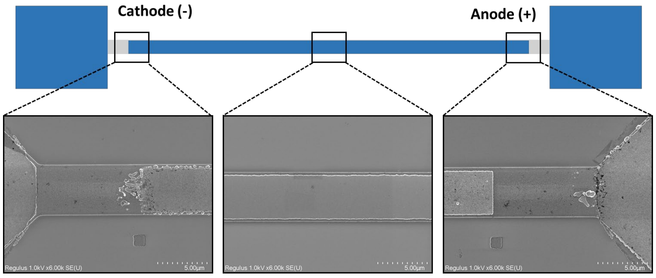

Figure 3.2. The test result of Cu stripes tested under the current density of 1 MA/cm^2 at 250 ºC for 3 hours

The elements analysis at the surface of the Cu film was examined using energy dispersive X-ray spectrometry (EDX). As shown in Figure 3.3 (a), the observed area is at the cathode end of the Cu lines, focusing on the distribution of Cu elements and potentially contaminated elements. Figure 3.3 (b) is the analysis of the copper, and figures 3.3 (c), (d), and (e) are the analysis of the titanium, oxygen, and silicon, respectively. The signal of the copper element is intense and unique on the interconnect surface, indicating that there is no observable contaminating element, and the large particles around the interconnect are indeed copper.

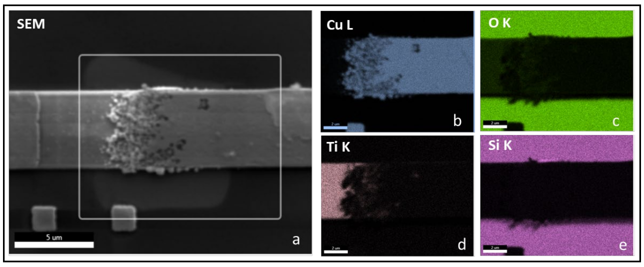

Figure 3.3. EDX mapping results of Cu stripe tested under the current density of 1 MA/cm^2 at 250 ºC for 3 hours

A. *Mechnisam of Local Dewetting*

Considering the fact that the 200 nm thick copper dewetting occurs at ≥550ºC, we believe that the copper has poor contact with the underlying TiN layer, which provides an additional local joule heating effect. We assume the poor contact between TiN and Cu film is due to the formation of a thin oxide layer on the TiN surface. During the TiN patterning process, the photoresist removal is carried out under low-pressure plasma in oxygen, which results in the formation of a thin oxide layer on the TiN surface. Therefore, the contact resistance increases and leads to instability of the interface. Also, in the early stage of EM, the gradual formation of the voids at the cathode side results in poorer interfacial contact than the anode. When a high current is applied to the structure, a large amount of Joule heat will generate at the relative highly resistive TiN/Cu interface. This results in a temperature gradient across the metal interconnect and gives to dewetting a direction. When the temperature caused by the Joule heating and the applied temperature is superimposed over 550 ºC, the local dewetting will start.

To verify the hypothesis, we fabricate a new structure without the thin oxide layer between the interface. Before the deposition of Cu film, a hot sputtering etch (HSE) process is employed to remove the thin oxide on the wafer surface.

Then the wafer is transferred to another chamber where 200 nm thick pure copper is deposited. The etching, transport, and deposition processes are performed in vacuum systems to prevent oxidation on TiN. We define this test structure as a TiN/Cu system, while the structure with the thin oxide layer as a TiN/Oxide/Cu system. The results obtained from the TiN/Cu system with the applied current density of 2 MA/cm^2 at 250ºC are shown in Figure 3.4. After 30 hours, a few small voids can be observed at the cathode side, and the void size increases with the stripe length. There was no dewetted copper observed around the interconnect.

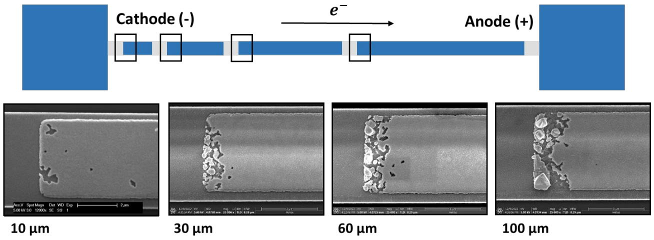

Figure 3.4. Test results for different lengths of Cu strips with TiN/Cu system under the current density of 2 MA/cm^2 at 250ºC for 30 hours.

B. *High Temperature Test in TiN/Cu System*

The high temperature EM test was carried out in the TiN/Cu system as shown in Figure 3.5. The EM test was at 550 ºC under a current density of 1 MA/cm^2 for 1 hour. The dewetted copper can be observed around the cathode side, which is similar to the results tested at 250 ºC in the TiN/Oxide/Cu system. The result suggests that in a high-temperature EM test, even without the native oxide layer, local dewetting still occurs on the cathode side due to the high applied temperature and electromigration. This high-temperature test also verifies our hypothesis that when a high current density is applied, the existence of the interfacial oxide layer causes a local temperature rise and the dewetting of Cu film. In addition, we found that the agglomeration of copper on the cathode side was less than in the TiN/Oxide/Cu system. This phenomenon can be explained by the presence of the oxide layer, which provides the driving force for dewetting by minimizing the total free energy of the metal-substrate interface [11].

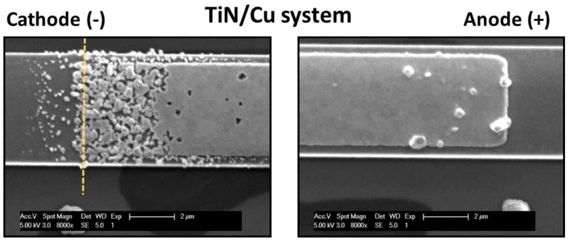

Figure 3.5. Test results for 100 µm Cu strips with TiN/ Cu system at 550 ºC under the current density of 1MA/cm^2 for 1 hour.

C. *Effect of temperature*

Figure 2.6 shows the test result for a sample with TiN/Oxide/Cu structure at different temperatures under a current density of 1 MA/cm^2 for 3 hours. At the cathode side, the void sizes increased with the temperature, and the size of the copper particles forming around the interconnects is also increased. This observation can be understood from the fact that electromigration and local dewetting are essentially thermodynamic enhanced processes; thus, the atomic diffusion movement is faster at a higher temperature.

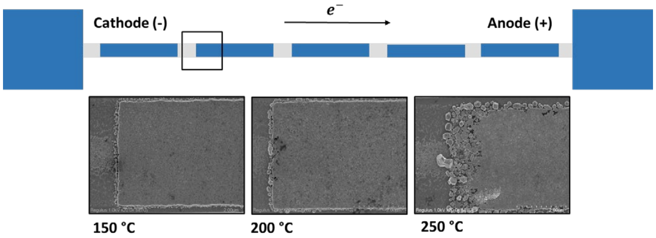

Figure 3.6. Test results for the sample containing 5 segments with the same length of 60 µm in TiN/Oxide/Cu system at different temperatures under the current density of 1 MA/cm^2 for 3 hours.

D. *Size effect*

Figure 3.7 shows the test results of Blech structure with TiN/Oxide/Cu system, containing stripes from 10 µm to 100 µm tested simultaneously, where voids at the cathode side can be observed. Under the same current density, the size of the voids becomes larger when the strip length increases. This observation is consistent with classical EM test results using Blech structure [13], suggesting the presence of EM during the test. In addition, at the cathode side, as the length increases, local dewetting becomes more pronounced, and more copper particles around the conductor can be observed. This result implies that in this experiment, the dewetting is affected by the EM effect.

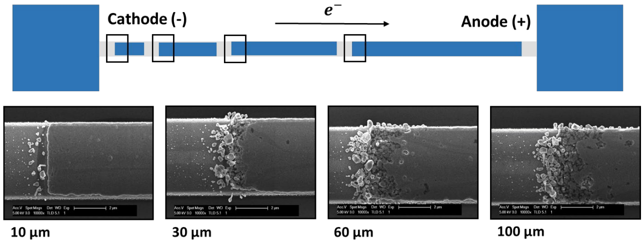

Figure 3.7. Test results for 10/30/60/100 µm Cu strips with TiN/Oxide/Cu structure under the current density of 1 MA/cm^2 at 250 ºC.

IV. CONCLUSION

This paper presents and discusses the local dewetting of Cu film during the EM test. This local dewetting occurs at a lower externally applied temperature where dewetting normally will not occur. We infer that the interfacial oxide layer promotes the dewetting of the thin copper film. This is because the oxide layer generated significant local Joule heating, and this provides the driving force for dewetting by minimizing the total free energy. We verified the hypothesis by testing the structure without the oxide layer. At 250 ºC, even with a higher current density, local dewetting was not observed at the cathode side. Finally, we investigated the size effect and temperature effect on local dewetting and EM. As the stripe length increases and temperature increases, local dewetting becomes more significant.

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