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DOI
10.1109/ECTC51529.2024.00214

Publication date
2024

Document Version
Final published version

Published in
Proceedings - IEEE 74th Electronic Components and Technology Conference, ECTC 2024

Citation (APA)
Zhang, Y., Yan, Y., Vollebregt, S., & Zhang, G. (2024). In Situ Analysis of Copper Microstructures in Electromigration Using SEM-EBSD Techniques. In *Proceedings - IEEE 74th Electronic Components and Technology Conference, ECTC 2024* (pp. 1317-1321). (Proceedings - Electronic Components and Technology Conference). IEEE. https://doi.org/10.1109/ECTC51529.2024.00214

2024 IEEE 74th Electronic Components and Technology Conference (ECTC)

2024 IEEE 74th Electronic Components and Technology Conference (ECTC) | 979-8-3503-7598-5/24/$31.00 ©2024 IEEE | DOI: 10.1109/ECTC51529.2024.00214

In Situ Analysis of Copper Microstructures in Electromigration Using SEM-EBSD Techniques

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The continuing drive to miniaturise electronic devices requires an understanding of how the materials in these devices behave under stress, particularly with respect to electromigration. In this study, we explore the relationship between the microstructure of copper (Cu) and electromigration by using an approach that combines in situ Scanning Electron Microscopy (SEM) with Electron Backscatter Diffraction (EBSD). This in-situ SEM-EBSD technique enables real-time observation and analysis of electromigration-induced microstructure changes. Our investigation provides detailed insights into the microstructure effect on electromigration. Specifically, samples annealed at 300 °C showed void formation after the electromigration test and higher Kernal average misorientation (KAM) values, indicating higher internal strains and an inhomogeneous microstructure. In contrast, samples annealed at 500 °C maintained lower KAM values with minimal changes in crystal orientation, highlighting a more stable and uniform electromigration-resistant microstructure. Our results demonstrate the critical role of microstructure in determining the electromigration resistance of copper interconnects. By optimizing the annealing temperature, the reliability of the copper microstructure can be significantly improved by reducing the dislocations and increasing grain size, thus extending its lifetime.

Keywords—electromigration, microstructure, grain, copper, EBSD.

I. INTRODUCTION

With the demand for the miniaturization of electronic devices in the semiconductor industry, the number of components required to be integrated into a single chip has increased. This leads to narrower interconnects and higher current density. Under this trend, electromigration has become one of the significant reliability changes encountered by electronic devices [1-6]. Electromigration (EM) is a phenomenon of mass transport due to the momentum transfer of electrons and metal ions in the conductor under the action of high current density. EM causes the depletion and accumulation of metal atoms within the interconnect, creating voids and hillocks that can further lead to shorts or opens in the circuit[7-9].

Microstructural analysis has become an important direction in gaining a deeper understanding of the impact of electromigration on metal interconnects. In aluminium-based interconnects, the grain boundaries are fast diffusion paths and therefore, electromigration occurs mainly along the grain boundaries. Zhen et al. [10] studied the effects of grain size and temperature on effective diffusivity and grain boundary diffusivity and calculated the values of these two parameters in aluminum stripes. In addition, microstructure and grain orientation are believed to have a significant influence on the location of electromigration damage. The mechanism of void nucleation and the effects of grain size, grain orientation, and dislocations on electromigration in Al-based interconnects were investigated using in situ techniques [11-13].

In copper-based interconnects the dominant mechanism of electromigration differs from that observed in Al or Al-alloy conductors. The surface and interface diffusion also play critical roles in electromigration behaviour, especially in different structures. E. linger et al. employed in situ techniques to analyse void growth in copper damascene lines, revealing surface diffusion as the primary diffusion path for void growth and determining an electromigration activation energy of 0.9±0.1 eV [14]. His results showed that the void growth rate is independent of linewidth, linking electrical resistance changes to physical void development. The EM of Cu nanowires has been studied by Q. Huang et al. with resistance measurements and in situ scanning electron microscopy [15]. The study found activation energies of 1.06 eV and 0.94 eV for copper wire widths of 90 nm and 141 nm, respectively, and showed that Cu mass transfer during electromigration occurs mainly along the wire surface. For passivated damascene Cu interconnect, Z-S. Choi [16] performed in situ observations. The results showed two EM failure modes: void formation at the cathode via and at distances from the cathode. Post-failure EBSD analysis revealed that voids initially grow at grain boundaries before drifting towards the cathode. This suggests that failure kinetics and reliability predictions must take into account both the location of void formation and its interaction with the microstructure. In addition to in situ SEM, C. N. Liao et al. [17] observed atomic-scale electromigration in thin copper lines using in situ transmission electron microscopy at temperatures below 100°C. It was determined that the interplay between planes and <110> directions in crystalline copper significantly impacts electromigration resistance, primarily due to anisotropic diffusion and electrical properties. Notably, mass transport induced by EM showed a strong preference for the Cu grains with (111) orientation.

Although extensive research has focused on the EM phenomenon in copper-based interconnects, using various analytical techniques to understand its mechanisms, significant gaps remain. The dynamic interplay between electromigration-induced mass transport and the evolving microstructure of copper lines remains uncharacterized. In this study, we conducted an in-depth analysis of the copper microstructure under electromigration stress by using in situ SEM and EBSD technology. We focused on the evolution of misorientation,

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DOI 10.1109/ECTC51529.2024.00214

grain size, and grain orientation during electromigration. This provides us with the opportunity to deepen our understanding of the effects of electromigration on the microstructure of copper interconnects.

II. EXPERIMENTAL PROCEDURE

A. *Test structure and EM process*

Samples were fabricated using the process in Ref [18]. A hot sputter etch was performed to remove the thin oxide layer on the TiN prior to copper deposition. In addition, chips were annealed in a vacuum chamber with N_2 and H_2 at 300 °C and 500 °C for 1 hour. The layout of the Cu lines is shown in Fig. 1. The test structure consisted of five individual copper lines with the Blech structure, each 100 μm long and five μm wide, connected in series. In the Blech structure, each line is equipped with its own cathode and anode, simplifying the observation of voids and hillocks that form following the electromigration test. In the EM test, since Cu has a much greater conductivity than TiN, the stressing current mainly flows into the Cu layer. This guarantees the occurrence of electromigration within the Cu layer. The dimensions of 5 μm width and 200 nm thick Cu stripes were stressed with a constant current density of 3 MA/cm^2 under ambient conditions of 250 °C and 300 °C. To prevent oxidation, the electromigration was carried out a vacuum at 5×10^{-6} mbar.

B. *In situ SEM*

The in-situ setup enables real-time observation during the electromigration process, specifically, it consists of a heating stage and a probe system. Fig. 1 shows a schematic overview of the measurement setup. The micro heating stage (Kleindiek MHS450) can be mounted on the SEM (XL30 SFEG) stage. It is equipped with a temperature control unit that enables precise temperature adjustments from ambient levels to a maximum of 450 °C, facilitating various experimental conditions. Add to this is the probe system, including two advanced Kleindiek MM3A-EM micromanipulators and a controller. These micromanipulators offer a sub-nanometer resolution of 0.25 nm, enabling it to probe contacts on small pads effectively, and probe current can range from 10 nA to 100 mA. This combination of precise temperature control and high-resolution probing positions makes the setup an ideal solution for exploring the intricate dynamics of electromigration in micro-scale Cu stripes.

C. *EBSD analysis*

After the electromigration test, the EBSD measurements were performed to study the microstructural characteristics of the samples. The experiments were carried out using an EDAX DigiView-5 camera and with OIM Anslysis 8.3 software. To ensure optimal interaction of electrons with the sample and obtain high-quality diffraction patterns, the sample was tilted to an angle of 70°. Analyses were performed at a working distance of 12 mm. This distance was chosen to provide a balance, allowing the EBSD detector to capture backscattered electrons efficiently while maintaining a clear diffraction pattern. EBSD maps were taken with 20 kV and scan step size between 0.15 and 0.20 μm.

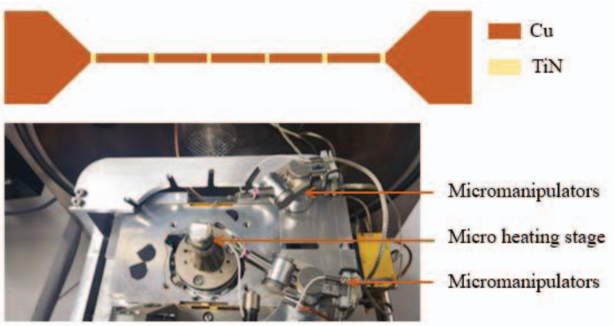

Fig. 1. Schematic diagrams for the test units and in situ setup.

III. RESULTS AND DISCUSSION

A. *In situ measurements*

The in-situ experiment was carried out at a temperature of 300 °C and a current density of about 3 MA/cm^2. Fig. 2 shows SEM micrographs of the cathode of 300 °C annealed Cu stripes for test times of 2, 4, 6, 8, 10, 15, 20, 25 and 30 min, respectively. The Cu stripe begins to form the voids at 4 min. Initially, these voids appear as tiny discontinuities on the Cu film surface. As the test progresses, these voids gradually increase in size, and after 30 min, the voids become more pronounced. During the electromigration testing period, our observations did not reveal the formation of new voids at the stripe edges. Instead, we observed the expansion of pre-existing voids.

In addition to the 300 °C annealed samples, our study investigated the electromigration behaviour of 500 °C annealed strips. These samples subjected to a higher annealing temperature exhibited a significantly reduced electromigration, with voids initiating at the cathode side after 15 min. Notably, compared to the samples annealed at 300 °C for 30 min, the voids were significantly smaller. The evolution of the initial voids is similar; no new voids were found to be formed in the cathode. These findings from in situ experiments revealed that annealing temperature affects the material's resistance to electromigration, which is attributed to the changes in the microstructure of the material caused by the annealing process. Therefore, it is essential to understand the influence of different microstructures on electromigration.

B. *Microstructure effect on EM*

EBSD analysis indicated the corresponding grain structure and out-of-plane crystal orientation of these samples. Due to the small grain size of the as-deposited Cu stripes, EBSD analysis was not possible. By examining the microstructural changes at annealing temperatures, 300 °C and 500 °C, we observed a significant increase in grain size with the rise in annealing temperature. Fig. 4 shows the grain map and grain size distribution of Cu stripes annealed at 300 °C and 500 °C. From the comparison of the grain maps of the two samples, we can clearly see the difference in grain size. At the lower annealed temperature of 300 °C, the average grain size was measured to be 143 nm. Upon increasing the temperature to 500 °C, the average grain expanded to 201 nm. Fig. 5 is the inverse pole figure map, indicating that the predominant crystal orientation of the sample annealed at 300 °C is primarily (111). Following a 5-hour electromigration test conducted at a current density of 3 MA/cm^2 at 250 °C, the cathode, anode and the centre areas of the Cu stripes were reanalysed, and there was no significant alteration in the crystal orientation. Similarly, samples annealed at 500 °C exhibited comparable results, as shown in Fig 6. In addition, there was no significant change in grain size before or after electromigration.

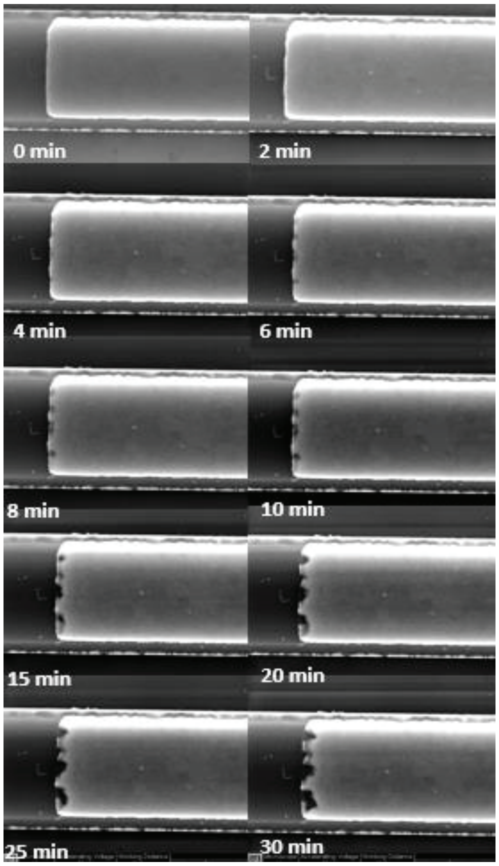

Fig. 2. SEM sequence that shows the evolution of voids at the cathode side of Cu stipes annealed at 300 °C. The EM stress is 30 mA at 300 °C.

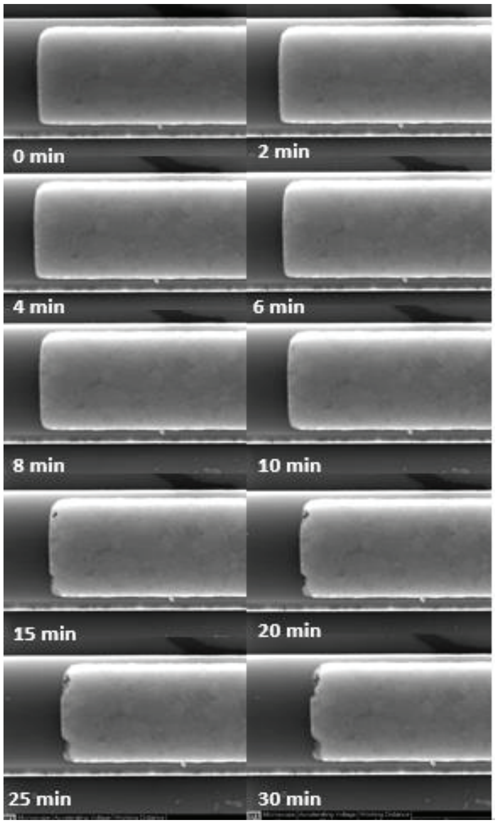

Fig. 3. SEM sequence that shows the evolution of voids at the cathode side of Cu stipes annealed at 500 °C. The EM stress is 30 mA at 300 °C.

In addition to grain size and crystal orientation, our study further investigates microstructural dynamics through Kernal average misorientation (KAM) values and grain boundary characteristics, particularly in electromigration effects. We conducted the microstructural study on three sections of the Cu stripes: the cathode, the anode, and the middle. Fig. 7 shows the Cu stripe annealed at 300 °C. The KAM values before and after electromigration are relatively similar and do not change significantly. Furthermore, a comparative analysis of the initial and post-electromigration KAM images revealed the formation of initial voids in the red region with high misorientation angles at the cathode edge of the copper stripe. When examining the middle part of the Cu stripes, we observe no significant microstructure changes, indicating that the local effects of electromigration mainly occur at the cathode side. This stability suggests that electromigration effects are not uniformly distributed across the stripe.

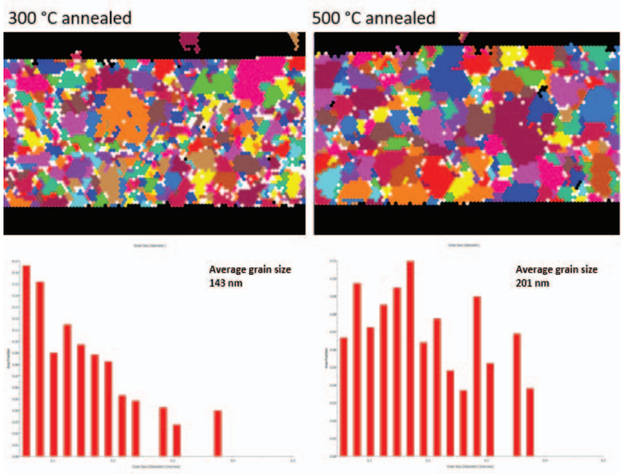

Fig. 4. Grain map and grain size distribution of 300 °C annealed and 500 °C annealed Cu stripes.

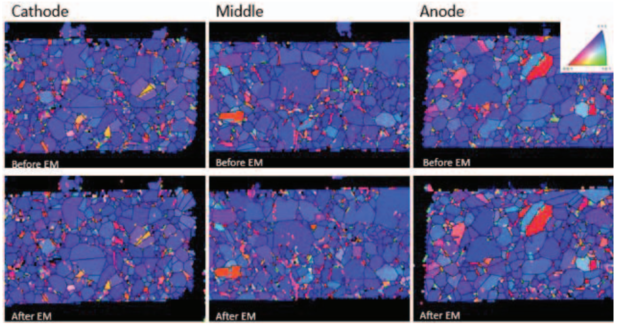

Fig. 5. Crystal orientation maps of 300 °C annealed Cu stripes before and after electromigration.

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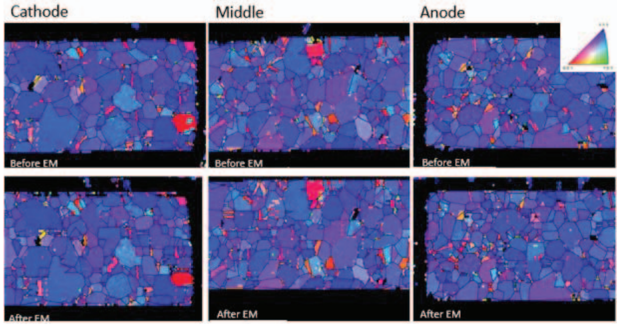

Fig. 6. Crystal orientation maps of 500 °C annealed Cu stripes before and after electromigration.

For samples annealed at 500 °C, the in situ results indicate that the microstructure affects electromigration. Fig. 8 shows that for Cu stripes annealed at higher temperatures, the overall KAM value is significantly lower, and the red areas of high misorientation are much reduced, indicating minimal internal strain and a highly uniform microstructure. Compared with the initial stage, post-electromigration analysis did not show a significant increase in KAM values, suggesting a possible resistance of the sample to internal strains and microstructural inhomogeneities caused by atom migration or EM cannot be observed from this test condition.

Furthermore, in contrast to the observations made on the 300 °C annealed samples, the 500 °C annealed strips did not exhibit obvious void formation at the cathode edge after the 5 h EM test, previously observed in high misorientation angle regions. The presence of such early voids, particularly at the cathode, suggests that the higher annealing temperature confers greater resistance to electromigration. Examination of the central area and anode area of the copper strip confirmed this finding, showing no significant microstructural changes after electromigration.

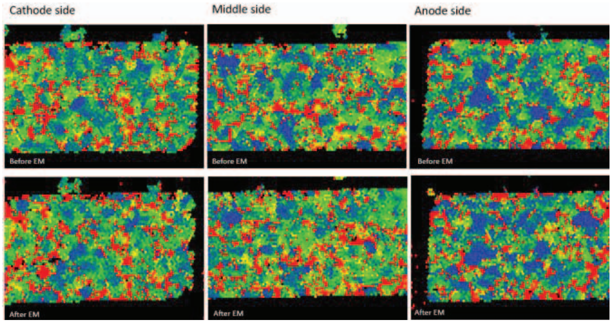

Fig. 7. Kernal average misorientation figure of 300 °C annealed Cu stripes before and after electromigration.

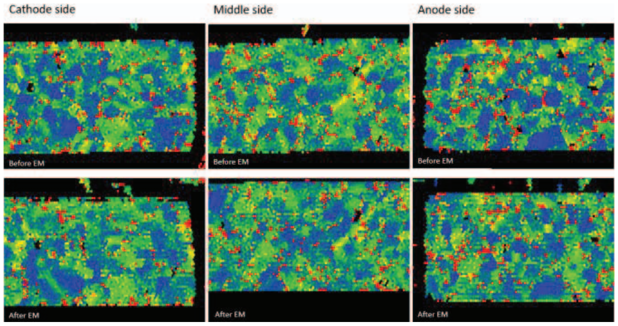

Fig. 8. Kernal average misorientation figure of 500 °C annealed Cu stripes before and after electromigration.

IV. SUMMARY AND CONCLUSIONS

In summary, our study started with in-situ observations that revealed the dynamic nature of electromigration in copper interconnects and provided insights into how microstructure affect electromigration resistance. These in-situ results showed an important need for more detailed microstructural analysis to fully understand the mechanisms involved.

Consequently, EBSD analysis was used to further investigate the microstructural changes induced by different annealing temperatures and their effect on the electromigration behaviour. We observed that samples annealed at 300°C exhibited early signs of electromigration-induced degradation, with an increase in KAM values and void formation only at the cathode edges. Conversely, samples annealed at 500°C showed an apparent resistance to electromigration. The EBSD results showed minimal changes in the microstructures of these samples, with low KAM values and no significant changes in crystal orientation, even after 5 h electromigration test. This confirmed that higher annealing temperatures result in a more electromigration resistant microstructure, probably due to the formation of larger grains and a more uniform crystallographic texture.

Conclusively, The potential of the in-situ SEM-EBSD technique, as demonstrated in this study, extends far beyond the current findings. This technology can be instrumental in several other research areas within materials science and engineering, offering profound implications for innovation and development. For example, the technique is ideal for studying phase transformations in real-time, providing insights into the kinetics and mechanisms of solid-state transformations in alloys; in addition, it can be used to study thermal stability in advanced materials, proving data on grain growth, phase stability, dislocation under thermal stress.

ACKNOWLEDGEMENT

Financial support by the iRel40 Project is acknowledged gratefully. iRel40 is a European co-founded innovation project that has been granted by the ECSEL Joint Undertaking (JU) under grant agreement NO876659. The funding of the project comes from the Horizon 2020 research programme and participating countries. National funding is provided by Germany, including the Free States of Saxony and Thuringia, Austria, Belgium, Finland, France, Italy, the Netherlands, Slovakia, Spain, Sweden, and Turkey.

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