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Line Scaling Effect on Grain Structure for Cu Interconnects

Lijuan Zhang, Jay Im and Paul S. Ho

*Laboratory for Interconnect and Packaging, Microelectronics Research Center
The University of Texas at Austin, TX 78712*

Abstract. The effect of line scaling on Cu grain structures has been investigated by using both plan-view and cross-sectional transmission electron microscopy (TEM) techniques. Cu damascene lines with three different line widths of 850, 185 and 60 nm were studied. The plan-view TEM images revealed that the 850 nm lines had both polycrystalline and bamboo-like grain structures, whereas the 185 and the 60 nm lines had near bamboo-like structures. Statistical analysis was performed on the grain size distributions for both 185 nm and 60 nm lines. The results showed that the 185 nm lines followed a normal grain growth behavior, while the 60 nm lines deviated from normal grain growth with excessive small grains at the lower percentile which was attributed to scaling-induced small grain growth. Further analysis by cross-sectional TEM along the Cu trench line direction revealed that the 850 nm lines had bamboo-like structures across the thickness while the 185 nm and the 60 nm lines showed a combination of bamboo-like and multigrain structures with small grain clusters concentrated at the trench bottom.

Keywords: Cu Interconnects, Plan-view TEM, Cross-sectional TEM, Grain, Microstructure.

INTRODUCTION

Copper has been widely used as interconnect material for high performance ultra-large scale integrated circuits (ULSIs) due to its superior electrical conductivity and robust electromigration (EM) reliability. Through the damascene process, Cu has been successfully implemented into ULSI chips. Extensive data have been published¹⁻⁴ on the microstructure of damascene Cu lines regarding the grain texture and size distribution and their variations with different line widths. Nevertheless, only few results have been reported recently⁵⁻⁸ on the microstructures of Cu lines narrower than 100 nm. For ultra-narrow Cu lines less than 100 nm wide, the resistivity was found to increase as the line width scales down. This effect was attributed to the increase in electron scattering caused by the surface, the interface and the grain boundary when the line width is approaching the electron mean free path in Cu (45 nm at room temperature⁵). For ultra-narrow Cu lines, there is a serious reliability concern arising from insufficient grain growth⁷. This can increase the grain boundaries, leading to an increase in resistivity and a degradation of the EM reliability. The degradation in EM lifetime was indeed observed recently for Cu lines at 90 nm line width and the effect was attributed to additional fast mass transport along the grain boundaries⁹.

In this paper, we investigated the scaling effect on the grain structure for Cu lines using transmission electron microscopy (TEM) techniques. The study was performed on Cu damascene lines of 60 nm line width fabricated by using a trench filling technique together with Cu lines with widths of 185 nm and 850 nm. Microstructures of Cu lines were examined by using both top-view (plan-view) and side-view (cross-sectional) TEM. With the resolution provided by TEM, grains of size smaller than 10 nm can be readily observed and analyzed.

EXPERIMENTAL DETAILS

The Cu interconnects were fabricated by SEMATECH using standard damascene process. The intermetal dielectric (IMD) material was silicon oxide (SiO_2). To produce very narrow lines, a SiON filling layer was deposited after the formation of line trenches in the SiO_2 dielectric. This was followed by Ta barrier and Cu seed deposition and Cu electroplating. Then after Chemical Mechanical Polishing (CMP), SiNx and dielectric layers were deposited as capping layer and passivation to protect the Cu lines. The Cu lines used for this study were 850, 185 and 60 nm in width, 110 nm in height, and 150 μm in length. Figure 1 shows the schematic layout of the sample.

FIGURE 1. (a) Cross-sectional illustration of Cu trench with SiON filling. (b) Schematic of fabricated Cu interconnect sample.

Both plan-view (top view) and cross-sectional (side view) TEM samples were prepared to study the Cu grain structure along the Cu line direction. Figure 2(a) shows a schematic illustration of the sample. Planar TEM sample was prepared using a conventional method consisting of the following steps: 1) cutting out a 2 mm square specimen with Cu line structure almost at the center; 2) gluing the specimen to a 3 mm radius Ni grid (a single hole in the center) using M-bond 610 adhesive; 3) polishing specimen down to ~ 100 μm thick using the diamond grit paper. The specimen thickness was roughly controlled by using Gatan Disc Grinder; 4) dimple grinding specimen to approximately 5 μm thick and 5) ion milling the specimen until electron transparency is reached using Gatan Precision Ion Polishing System (PIPSTM). The resulting TEM sample consisted of Cu lines confined with Ta diffusion barrier at both side walls. The top nitride passivation layer and bottom barrier layer have already been removed during the ion milling process. Figure 2(b) shows a schematic drawing of the plan-view TEM sample.

Site specific cross-sectional TEM sample was prepared using Focused Ion Beam (FIB) technique¹⁰. A 2.5 mm wide and 100 μm thick specimen strip was first prepared using the dicing saw. Before FIB milling, a 200 nm wide and 500 nm thick Pt strip was deposited on the target area to protect Cu lines from damage during ion milling. Then the 100 μm -thick specimen was thinned from both sides down to less than 100 nm thick by using Ga ion beam. A FEI Dual Beam FIB equipped with an electron gun allowed the direct observation of the milling process. Final cleaning was done with 30 KeV/10 pA beam to minimize beam damage to the target area. Figure 2(c) is an SEM image of one well-prepared TEM sample by FIB. TEM images were taken using JEOL 2010F and FEI TECNAI G2 F20 microscopes operating at 200 KeV.

FIGURE 2. (a) Schematic diagram showing plan-view (top view) and cross-sectional (side view) observations of Cu interconnects using TEM. (b) Schematic drawing of the plan-view TEM sample. (c) SEM image of one well-prepared cross-sectional TEM sample.

EXPERIMENTAL RESULTS

Plan-view (top-view) TEM Observation of Cu Line Microstructure

Figure 3 shows the plan-view TEM images of Cu interconnects with line widths of (a) 850 nm, (b) 185 nm, and (c) 60 nm. Distinct differences in the Cu microstructure can be observed for different line widths. While the 850 nm lines had both bamboo-like and multiple grain structures, the 185 nm and the 60 nm lines had predominately bamboo-like structures with the presence of microtwins. Statistical grain analysis on grain size distribution was carried out on the 185 nm and the 60 nm wide lines and the results are shown in Figure 4. The grain size was calculated as the diameter of the grain area by assuming the grain to be of circular shape. It shows that the average grain size scaled as the Cu line width decreased from 185 nm to 60 nm. It is also observed that the narrow 60 nm lines had a higher population of small grains. This observation is consistent with the results reported in previous work⁹.

FIGURE 3. Plan-view TEM images of (a) 850, (b) 185, and (c) 60 nm wide Cu lines.

FIGURE 4. Grain size distribution of 185 nm and 60 nm wide Cu lines.

Cross-sectional (side-view) TEM Observation of Cu Line Microstructure

Figure 5 shows the cross-sectional (side-view) TEM images of Cu interconnects with line widths of 850, 185 and 60 nm. In Figure 5(a), the 850 nm lines show bamboo-like grain structures across the line thickness along the Cu line direction. In Figures 5(b) and 5(c), the 185 nm and the 60 nm lines have both polycrystalline and bamboo-like grain structures throughout the trench line. Some sections of the line were observed to have one single grain spanning the thickness, while other sections showed multiple grains across the thickness with more small grains at the trench bottom. No significant difference in the microstructures of the 185 nm and the 60 nm lines were observed in our study. However, narrower lines have been reported to have more small grains due to the larger proportion of PVD Cu seed at the trench bottom during Cu deposition which prohibited extensive grain growth to bamboo-like structure⁹.

FIGURE 5. Cross-sectional TEM images of (a) 850, (b) 185, and (c) 60 nm wide Cu lines.

Grain growth in general is driven by minimization of energies, including that associated with the lattice, elastic, interfacial and grain boundaries. With scaling increasing the interface to volume ratio, interfacial pinning at the sidewalls and trench/via bottoms is expected to become more effective in anchoring small grains. This will favor the formation of small grains near the line bottom as the line width decreases, as observed in our TEM study. Since the distribution of the small grains is random, this raises an interesting and important question regarding the small grain effect not only on EM lifetime but also on the statistics. A higher fraction of Cu atoms at the grain boundaries and an increased number of fast diffusion paths will increase the void growth rate caused by EM and since the damage site depends on the small grain distribution, this in turn affects the EM lifetime statistics.

CONCLUSION

Ultra-narrow Cu interconnects were fabricated by damascene process with a trench filling of SiON layer and their microstructures were investigated. Both plan-view and cross-sectional TEM samples were prepared and investigated for Cu lines with line widths of 850, 185 and 60 nm. Plan-view TEM images showed that the 850 nm lines had both polycrystalline and bamboo-like grain structures. However, the 185 nm and the 60 nm lines had near bamboo-like grain structures. Statistical analysis of grain size distribution was performed and the results showed that compared with the 185 nm lines, the 60 nm lines had a larger population of small grains, which was attributed to scaling-induced small grain growth. TEM observation in the cross-sectional direction along the Cu lines showed that the 850 nm lines had bamboo-like grain structure across the line thickness while the 185 nm and the 60 nm lines had a mix of multigrain and bamboo-like structures with more small grains at the trench bottom. The presence of excessive small grains in the ultra-narrow Cu trenches was attributed to the interfacial pinning of small grains and a larger proportion of Cu seed at the trench bottom. The scaling effect of grain structure on EM lifetime and statistics raises an interesting and important question for EM study of future Cu interconnects.

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