Microstructure Analysis in As-deposited and Annealed Damascene Cu Interconnects using OIM

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Abstract. Microstructure variation with linewidth was studied for both as-deposited and annealed damascene Cu interconnect lines. Ten specimens with different linewidth and pitch distances were investigated using Orientation Imaging Microscopy (OIM). The microstructures, examined both before and after annealing, displayed high percentage of Σ3 boundaries. The microstructure was characterized by measuring the mean grain size, grain size distribution, grain boundary misorientation distribution and coincident site lattice (CSL) boundary distribution. The mean grain size increased proportionally until the linewidth was equal to line depth and slowly stabilized thereafter. The role of linewidth to pitch distance ratio was identified on influencing some of the microstructural features. The grain shape was analyzed using the grain aspect ratio parameter. The strain distribution in the line was studied using image quality (IQ) parameter.

INTRODUCTION

After the replacement of Al by Cu as an interconnect material, much research has been done to understand the behaviour of Cu in narrow trenches. There have been many reports which detail the microstructure evolution using texture as characterization tool but not much data has been published with regard to the grain size, shape and distribution especially for Cu damascene lines. These parameters have an important role in deciding the stress voiding and electromigration behaviour of Cu. The investigation of these parameters is even more significant taking into account the metastable nature of Cu film upon electrodeposition wherein the phenomenon of self-annealing is observed at room temperature [1]. Hence, annealing is a very important step in controlling the final texture and microstructure of the Cu lines. As a result, it is of great interest to study the microstructure in the Cu lines in as-deposited condition itself and its evolution upon annealing. The present paper describes the investigations done on both as-deposited and annealed Cu lines, which gives more clear illustration of overall change occurring as a function of linewidth and also microstructure evolution upon annealing.

EXPERIMENTAL

Ten specimens with different linewidth and pitch distances were investigated using OIM apparatus attached with Philips XL-30 field emission gun scanning electron microscope. The linewidth/pitch distances were 0.35/0.35, 0.4/3.6, 0.5/0.5, 1/1, 3.6/0.4, 4/36, 10/10, 36/4, 40/360 and 100/100 μm. The interconnects were deposited in an area spanning 2.5 x 1.75 mm² and were tested in as-deposited condition (however, over a period of time they may have undergone recrystallization at room temperature) and after annealing at 400°C for 30 min. Annealing was performed after CMP and deposition of top passivation layer. Measurements were done at 20 kV, specimen tilt of 70° and working distance of 15 mm. The underlying Cu lines were exposed by removing the top passivation layer by etching in 15% HF for 5 minutes. The number of grains investigated via EBSD varied from 500 to 32,000 for all the lines giving a good statistics of
collected data except 0.4 and 1 μm lines where only 75 and 270 grains could be examined.

RESULTS AND DISCUSSION

Figure 1 reveals the grayscale OIM maps for the narrowest 0.35 μm lines in both as-deposited and annealed condition. Only small portion of the total scanned area has been displayed. Since the lines were highly twinned, as we show later in this paper, the maps were computed both before and after neglecting the presence of the Σ3 boundaries.

The OIM maps distinguish each grain from its neighbouring grains with a different grayscale color and give a more clear view of the grain shape and structure. As can be seen in figure 1, the grain structure is almost bamboo shaped at many places in both as-deposited and annealed lines. Also, larger grains in the annealed lines compared to as-deposited lines indicate grain growth having occurred during annealing.

Figure 2 depicts the mean grain size as a function of linewidth for both as-deposited and annealed states. The hypothetical straight line in the graphs shows the dimensions where the mean grain size equals the linewidth. The mean grain size was calculated by two methods – firstly, before neglecting the presence of Σ3 boundaries (considering twins as separate grains) and secondly, after neglecting the Σ3 boundaries (considering twins as part of grains). The mean grain size increased proportionally with linewidth for the narrower lines until the linewidth of 1 μm, which is close to the trench depth of 1 μm. This is mainly due to the influence of trench sidewalls and bamboo grain structure in the narrower lines. Beyond 1 μm the mean grain size slowly stabilizes due to the constraints imposed by neighbouring grains. The same observation was made by Jiang et al. [2].

An interesting observation that could be made from figure 2 is that though the 3.6 and 4 μm lines have almost the same width there is significant difference in their mean grain size. Similar is the case for higher linewidths of 36 and 40 μm and narrower linewidths of 0.35 and 0.4 μm. However, these lines had different pitch distances indicating the role of linewidth to pitch distance ratio on influencing the mean grain size.

Lower grain size in the 0.4 μm lines may also be attributed to the lower statistics of collected data since only single line was examined.

The grain size distribution was computed for all the specimens but has been represented for the narrowest 0.35 and one of the widest 10 μm lines for comparison in figure 3 in both as-deposited and annealed condition, considering twins as separate grains. The distribution is log-normal. Also, the distribution, upon annealing, shifts to the larger grain size which is relatively more significant for higher linewidths. The absence of this shift in the lower linewidths may be attributed to the recrystallization that may have occurred in these lines at room temperature due to lower pitch distance. The recrystallization led to the increase in the grain size in narrower lines in as-deposited condition. The role of pitch distances in inducing early recrystallization has
FIGURE 3. Grain size distribution for as-deposited and annealed (a) 0.35 and (b) 10 μm damascene Cu interconnect lines

been demonstrated by other authors [3].

Figure 4 reveals the grain boundary misorientation distribution for the 0.35, 0.5 and 36 μm lines. In all the cases we find the grain boundaries with misorientation between 55 to 60° to be present in significant fraction followed by the boundaries between 35 to 40°. The former are the Σ3 boundaries between the grains, which are rotated by 60° around the common <111> axis. The latter are the Σ9 boundaries between the grains, which are rotated by 38.5° around the common <110> axis. Also we find that the fraction of high angle grain boundaries with misorientation between 15 to 45°, which have high energy, has decreased upon annealing for most of the specimens, which indicates that some grain boundary migration has occurred during annealing. This effect was not seen in 36 μm lines indicating the role of pitch distance to linewidth ratio on affecting the grain boundary mobility.

Figure 5 compares the sum of the fraction of twin and twin variant boundaries in as-deposited and annealed lines. We find that the fraction increased upon annealing in most of the lines except the 3.6 and 36 μm lines, which also had the smallest pitch distance indicating the role of pitch distance in influencing the CSL distribution. Increase in the fraction of CSL boundaries upon annealing was also observed by Field [4].

The fraction of CSL boundaries was computed for all the lines (not shown here). Predominant presence of Σ3 boundaries was observed followed by Σ9, Σ27a, Σ27b and Σ7. Also as observed from figure 5 the fraction of
CSL boundaries was higher in the narrower linewidths compared to the higher linewidths which is a good sign since the role of these special boundaries in providing better electromigration resistance in the Al interconnects has been demonstrated [5].

It has been shown that the grain boundary planes normal to the trench sidewalls offer more resistance to electromigration compared to case when they are parallel [1]. In that aspect the measurement of grain shape may give more insight in predicting the electromigration reliability of the Cu lines. We measured the grain aspect ratio in the lines assuming the grains to be ellipsoids before and after neglecting

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\text{Aspect ratio} = \frac{b}{a}
\]

Figure 6 reveals the measurement scheme for the narrowest 0.35 μm lines wherein the imaginary ellipses have been superimposed on the grains.

Moreover the grains have been classified based on their aspect ratio with grayscale colors as shown in the legends besides the figures 6b and 6c. We define the grain aspect ratio as the ratio of the minor axis of the ellipse to its major axis.

Figure 7 shows the grain aspect ratio distribution in both as-deposited and annealed lines before and after neglecting \(\Sigma 3\).
FIGURE 7. Grain aspect ratio distribution for (a) 0.35 (b) 0.5 and (c) 36 μm as-deposited and annealed damascene Cu interconnect lines before and after neglecting the presence of Σ3 CSL boundaries.

One can see that the distribution is symmetric with higher fraction of the grains having aspect ratio between 0.4-0.6. The distribution shifts towards lower values upon neglecting the presence of Σ3 boundaries, which is more prominent for the narrower linewidths due to elongation of the grains along the trench length and increased influence of trench sidewalls.

The image quality (IQ) graphs were computed for all the lines but have been represented for only 0.5 and 10 μm lines (Fig. 8) since most of the lines showed the same behaviour. The IQ parameter is directly related to the strain distribution in the specimen though it also depends on other factors like orientation of the grains and sample surface condition. The higher grayness of IQ maps shows larger strains in the specimen (while higher IQ value shows less strain).

The higher IQ for the as-deposited lines indicates lesser strain distribution in these lines compared to annealed lines. This could be attributed either to higher stresses induced in the annealed lines due to different coefficient of thermal expansion between the Cu and surrounding barrier material on the chip or to improper surface condition.

FIGURE 8. IQ plot for as-deposited and annealed (a) 0.5 and (b) 10 μm damascene Cu interconnect lines.

CONCLUSIONS

The microstructure has been investigated in as-deposited and annealed damascene Cu interconnect lines. Microstructure was characterized by measuring the mean grain size, grain size distribution, grain boundary misorientation distribution, CSL boundary distribution, grain aspect ratio distribution and IQ plots. Additionally most of the parameters were analyzed before and after neglecting the presence of Σ3 CSL boundaries. Some important observations were noted and variations were observed upon annealing and also with change in linewidth. Role of linewidth to pitch distance ratio was identified on some of the parameters.

ACKNOWLEDGMENTS

One of the authors K. Mirpuri would like to acknowledge the support of NSERC-IPS, AESF, Joseph Stauffer and Horace G. Young graduate awards.

REFERENCES