Evolution of Grain and Micro-Void Structure in Electroplated Copper Interconnects

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1. Introduction

Electroplating is an attractive technology for fabricating copper interconnects at relatively low cost and high throughput.1–3 An important goal in producing interconnection lines which are highly reliable is to achieve films which have as large a grain size as possible, as well as being free from voids.4) Plating methods are capable of achieving large grain sizes in Cu lines, but even in annealed films, a distribution of smaller grain sizes exists. We have found that in 0.27 μm lines annealed at 350°C, a large number of grains with dimensions of less than 0.1–0.2 μm are still present. One of the goals of this work is to identify why such grains do not take part in grain regrowth. To do this we have examined the orientational relationship between such small stable grains and the surrounding larger grains for as-plated Cu lines, and for lines annealed in the range 150–350°C.

In addition, we have carried out a study of small micro-voids which are normally present in the as-plated lines, and examined their behavior during annealing in the temperature range 150–350°C. These voids are roughly spherical, and are typically 5–20 nm in dimensions. They are usually associated with the seam of the filled line, forming a band running along the central axis of the line, near to the top surface.

2. Experimental

Electroplated wafers were produced using a SemiTool LT-210 system. Cu line patterns with 0.27 μm line widths were used for this study. A large number of Cu lines were examined for grain size and micro-void analysis. Grain size analysis, in particular, requires a large statistical sample to reduce errors. All grain size distributions shown in this paper were obtained by measuring a sample population of at least 1000 grains. Grain sizes were generally evaluated from plan-view TEM specimens. For any given region, observations were carried out using at least three different specimen tilting angles.

The purpose of this was to ensure that all grain boundaries were in contrast, and that twins could be easily identified and eliminated from the grain count. The TEM images were obtained in digital format and grain counting was carried out by computer.

Grain orientations were determined by electron beam micro-diffraction analysis. An electron probe was placed on each grain and the resulting diffraction pattern was analyzed to determine the nearest low-index direction. Square micron in plan-view specimens, and void distributions were obtained by the line method, counting the number of grains intersecting an imaginary line drawn at any given location.

3. Results and Discussion

3.1 Grain Analysis

Figure 1 shows typical plan-view TEM images and grain size distributions for 0.27 μm wide lines. In Fig. 1(a) the data is for as-plated Cu lines, whereas in Fig. 1(b) the results following a 10 min anneal at 350°C are shown.

From the grain size distributions, the increase in average grain size during annealing is obvious. However, the distribution becomes broader and a sizable fraction of small grains still exist. For convenience, we categorize small grains as those which have dimensions less than 0.2 μm. This is reasonable since this is smaller than the line width of 0.27 μm, so these are never bamboo-type grains. Ideally, we would wish to have a uniformly large grain size to increase the resistance of the lines to electromigration and stress migration effects. Therefore the question is why some small grains are resistant to grain growth. What is the source of the stability of these grains? From results taken at higher annealing temperatures and for longer annealing times, we have found that these small stable grains are almost impossible to completely anneal out.

To help determine what is unique about these small stable grains, we have performed detailed micro-diffraction analysis to identify grain orientations for large and small grains. In
Fig. 1 Typical plan-view TEM images and grain size distributions for 0.27 µm lines; (a) as-plated lines containing a large number of small grains, (b) following a 10 min anneal at 350°C, causing an increase in average grain size.

Fig. 2 Percentage of large and small grains vs. annealing temperature. The lower curve isolates only small grains which have a high-index orientation.

In particular we have examined the orientation of small grains which are completely surrounded by larger grains without being absorbed by them. This kind of study was carried out for as-plated Cu lines and for lines subjected to anneals from 150–350°C. The results indicate that for large grains the major vertical orientations are (111) and (100). Although the smaller grains can also have these orientations, a large fraction of small grains do not, but instead have high-index orientations. The results are shown in Fig. 2.

In Fig. 2, the upper two curves show the percentage of grains which are larger and smaller than 0.2 µm for each annealing temperature. As the annealing temperature increases, the grain growth process causes small grains to be converted to or absorbed by larger ones, so the large grain population grows at the expense of the small grain population. The overall percentage of small grains decreases from about 45% in the as-plated condition to just 10% following a 350°C anneal. This is pretty much what we would expect. However, if we look only at small grains which have been determined to have high-index orientations, then the situation is different. In the as-plated film, some 11% of all grains fall into this category, and following the highest temperature anneal, this value has dropped only to 7%. This clearly indicates the thermal stability of these high-index small grains.

If we now examine the direct relationship between annealing temperature and grain orientation, we obtain the results shown in Figs. 3(a), (b). Note that the percentages in each figure refer to the percentage of large grains and percentage of small grains in Figs. 3(a) and (b) respectively, and not the percentage of all grains. In the as-plated lines, the dominant orientation for large grains is (111), with some (100) and high-index components. During annealing, the (111) orientation increases and other orientations decrease. Large grains with high-index orientations are rapidly removed (Fig. 3(a)). For small grains the situation is completely different. All low-index orientations disappear during annealing as these grains grow to join the population of large grains. Small grains with high-index orientations, on the other hand, very quickly come to dominate the small grain population.

These results lead us to conclude that grain orientation plays a major role in the grain growth process. Small grains which have orientations which greatly differ from that of surrounding larger grains cannot be easily absorbed by the surrounding grains. Nor do they appear to grow larger independently. Large grains with high-index orientations are very rare in annealed lines.

3.2 Micro-void studies

We use the term micro-voids to describe small voids with dimensions of typically 5–20 nm which we have found to be a common feature in plated Cu lines. The voids appear to be closely associated with the seam in a filled line, and form a band near the top surface running along the line axis. They are probably formed by incomplete closure of the seam. The seam itself results from side-wall growth during line filling.

Figure 4 shows typical examples of the appearance of these voids in 0.27 µm Cu lines, before and after annealing. These voids appear to be extremely resistant to any form of annealing, but the annealing process does cause a spatial redistribu-
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![Graph showing grain orientation vs. annealing temperature] Fig. 3 Grain orientation vs. annealing temperature for (a) large grains, (b) small grains.

![Image showing micro-voids in 0.27 µm Cu lines before and after a 10 min at 350°C anneal] Fig. 4 Micro-voids in 0.27 µm Cu lines before (left) and after (right) a 10 min at 350°C anneal.

![Graph showing density of micro-voids for different annealing temperatures] Fig. 5 Density of micro-voids for different annealing temperatures in the range 0–350°C.

4. Conclusions

An in-depth study has been carried out into two different aspects of the microstructure of plated Cu lines. Firstly, the reason for the persistence of very small grains in the lines, even after annealing, was investigated. It was found that a major influence on the exclusion of these grains from normal grain growth is their unusual orientation. They tend to have a high-index orientation in contrast to surrounding (111) or (100) grains. This may make grain boundary motion difficult.
In addition, we have examined micro-voids in the lines and correlated their redistribution during annealing with the movement of grain boundaries during the grain growth process.

REFERENCES