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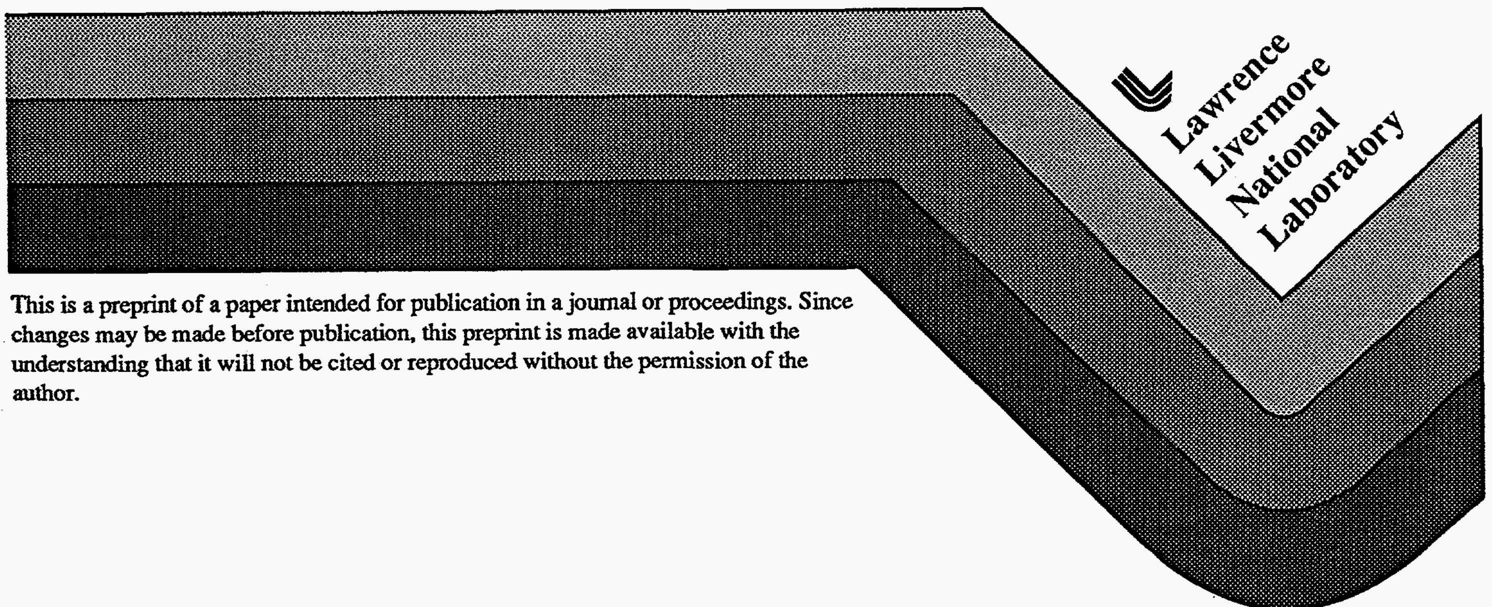

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MECHANISM OF ELECTROMIGRATION FAILURE IN AL THIN FILM INTERCONNECTS CONTAINING SC

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ABSTRACT

In order to understand the role of Sc on electromigration (EM) failure, Al interconnects with 0.1 and 0.3 wt.% Sc were tested as a function of post-pattern annealing time. In response to the evolution of the line structure, the statistics of lifetime evolved. While the addition of Sc greatly reduces the rate of evolution of the failure statistics because the grain growth rate decreases, the MTF variation was found to be very similar to that of pure Al. These observations seem to show that Sc has little influence on the kinetics of Al EM; however, it has some influence on the EM resistance of the line since it is an efficient grain refiner. Unlike Cu in Al, Sc does not seem to migrate, which may explain its lack of influence on the kinetics of Al EM.

INTRODUCTION

The addition of alloying elements to Al interconnects often results in improvements in their resistance against electromigration (EM) failure and has become a common method in modern device technology. With the increasing demand for more reliable and higher density interconnects, the development of new alloy systems has become one of the research interests in this field. For instance, new alloys, such as Al-V, Al-Pd and Al-Sc, were recently introduced [1-4].

Solute effects studies on EM failure are rather complicated and often difficult to interpret since the failure kinetics is determined not only by the overall EM kinetics but also by the microstructural details of the interconnect line such as the grain structure and the texture. For example, it is well known that the beneficial role of Cu is due to its influence on the overall EM kinetics; Cu decreases the kinetics of Al EM, as long as it is present in the migration path [5,6]. Nonetheless, it is possible to observe a prolonged lifetime in the Al interconnect, even if the solute has little effect on the overall EM kinetics when the solute enhances the development of homogeneous grain structures. This can be achieved either by uniformizing the grain size or promoting a particular grain texture. A solute which controls the kinetics of Al EM is more desirable than a solute which allows some control of the grain structure, particularly for the case of very narrow lines where the grain structure uniformity is limited by the line dimension.

We have attempted to isolate the two factors mentioned above using Sc as an alloying element. Previous reports have suggested that the addition of Sc can substantially enhance the EM lifetime [3]. We have found in this study that Sc actually has little effect on the kinetics of Al EM, and that its real influence on EM resistance is due to its influence on grain growth kinetics. Al-Sc lines with 1 μm width were prepared and tested after various post-pattern annealing treatments. The lifetime statistics changed with the evolution of the line structure. The results were then compared with the results for pure Al. A microstructural examination of failure sites was also performed to supplement our results.

EXPERIMENTAL PROCEDURE

In this investigation, Al films with two different Sc contents were used: 0.1 and 0.3 wt.%. Thin films, 0.5-μm-thick, were deposited by sputtering at room temperature onto Si

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substrates with 0.1-μm-thick thermal oxide. The films were patterned using a standard dry etching technique to produce test structures containing 25 1-μm-wide lines. The samples were annealed after patterning at two different temperatures (500°C and 550°C) for up to 2 hrs. The samples were air-quenched in order to retain the Sc in solid solution. The lines were then tested under a current density of 1.2×10^6 A/cm^2 at the substrate temperature of 225°C. Some of the lines were aged at 225°C for various times before testing. The median time to failure (MTF) and deviation of time to failure (DTF) were measured by fitting the lifetimes to log-normal distribution. A minimum of two independent tests were performed to validate each set of results.

RESULTS AND DISCUSSION

Microstructure

The microstructural examination of the film before anneal revealed that grains are smaller than 0.2μm and randomly oriented for both Al-Sc and pure Al. Grain growth in the Al-Sc alloy is different from that of pure Al; first, the kinetics of grain growth decrease as Sc concentration increases. Second, abnormal grain growth is more pronounced for Al-Sc films. Fig.1 shows the typical microstructure of an Al-0.3Sc after a 60 min. anneal at 550°C and aging for 20 hrs at 225°C. This TEM micrograph shows the bimodal nature of grain structure. Fig.2 also shows the bimodal distribution of grains developed in Al-01Sc by post-pattern annealing at 500°C for 60 min. It can be seen that fairly small grains are bounded by bamboo grains.

In general, solutes in Al alloys retard grain growth, since solutes tend to decrease grain boundary motion. The effectiveness of Sc as a grain refiner has been well characterized in previous studies [3]. Furthermore, the presence of Al_3Sc precipitates plays a more significant role on grain growth than Sc in solution. The solubility of Sc in Al is approximately 0.06 and 0.12% at 500°C and 550°C, respectively [7]. Therefore, Sc in the Al-0.1Sc alloy at 550°C should be in solid solution, while precipitates should form in Al-0.3Sc alloy. This can explain the grain growth kinetics differences between films containing 0.1 and 0.3Sc.

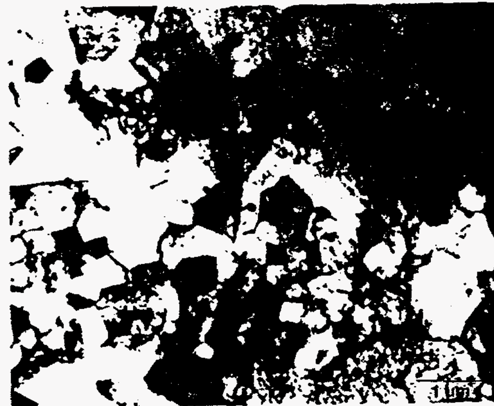

Fig.1 TEM micrograph showing a grain structure in Al-0.3Sc film, after 60 min. annealing at 550°C and subsequently aged at 225°C for 20 hrs.

TEM investigation of aged samples showed that precipitates formed inside the grains were coherent and disc shaped. Fig.1 shows stable incoherent precipitates along grain boundaries. With further aging, grain boundary precipitates coarsen by depleting Sc from the matrix. The coarsening kinetics were found to be very slow, probably because of the high stability of precipitates in the matrix. Even after several days of aging at 225°C, a large number of coherent precipitates were still present in the matrix.

Fig.2 TEM micrograph showing a line structure found in Al-0.1Sc, after post pattern annealing at 500°C for 60 min.

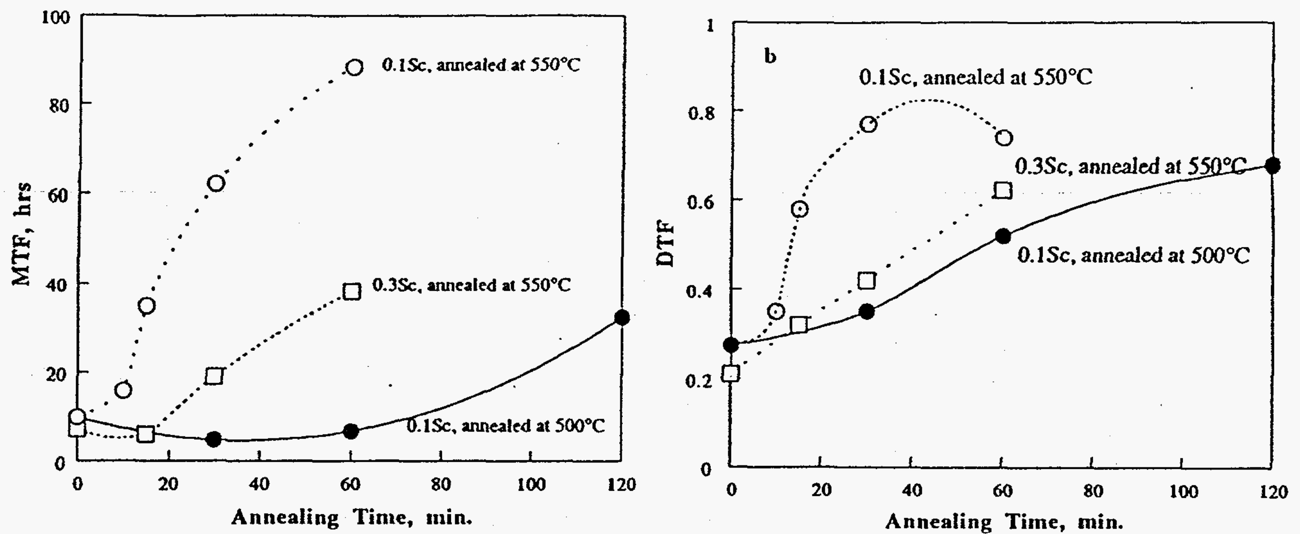

Fig.3 Variation of MTF (a) and DTF (b) as a function of post-pattern annealing time in Al-Sc interconnects.

Failure Mechanism in Al-Sc

EM failure in Al thin films occurs by void nucleation and growth where vacancies accumulate due to a divergence of flux in the microstructure [8]. Since grain boundary migration is the dominant transport mechanism at lower temperatures, the inhomogeneity in grain boundary distribution will provide preferential failure sites. When the average grain size is much smaller than the linewidth, the inhomogeneity is determined by the local arrangement of the grains. As the average grain size to linewidth ratio decreases, single grains start to span across the entire width, and the polygranular clusters become favored failure sites. Previous studies [9-12] have suggested that the lifetime of the line is inversely proportional to the length of the polygranular segment. Two types of studies have been conducted to investigate the effect of the microstructure on the EM lifetime and showed a strong correlation between linewidth to grain size ratio and failure statistics. The first method has been to vary the linewidth for a given microstructure [13,14]. The other method has been to induce grain growth (before or after patterning) but keep a constant line dimension, where annealing time is the control parameter which produces a variation in line structure [15]. We have used this method to perform independent investigations on the failure of pure Al interconnects with 1 μm linewidth [16]. In that study, we have found that the MTF initially decreases until bamboo grains appear to then rapidly increase due to the reduction of polygranular segment lengths. We also found that the scattering of the time to failure (i.e. DTF) monotonically increases before reaching a plateau.

The post-pattern annealing technique discussed above is useful in isolating the solute effect on overall kinetics from the effect on the microstructural evolution of the lines. The variation in MTF and DTF with annealing time is characteristic of the variation in the line structure, whereas the absolute magnitude of MTF depends on the overall kinetics of failure, which can be improved by the addition of solute elements. Applying this idea to Al-Sc alloys, we were able to conclude that Sc has very little influence on the overall EM kinetics. The results of the post-anneal tests are summarized in Fig.2, where the variation of MTF (a) and DTF (b) of Al-Sc alloys is plotted as a function of annealing time. The shape of the MTF and DTF vs. annealing time curve is similar to that of pure Al, though the variation rate is different and depends on the Sc

concentration and annealing temperature. In the case of pure Al, annealed at 480°C for up to 60 min. and tested under the same condition as the Al-Sc, the MTF ranged from about 2 hrs to well above 100 hrs. When the MTF in pure Al is compared to that in Al-0.1Sc annealed at 550°C, no magnitude difference is noticeable. The microstructural examination of failure sites confirmed that the failure mechanism in Al-Sc is virtually the same as that in pure Al. The lines containing the polygranular segments always failed at the end of the segment, irrespective of Sc content. Therefore, it is clear that the variation of MTF and DTF in Al-Sc by annealing are caused by the change in the line structure. The same conclusion can be drawn by comparing the results for 0.1 and 0.3Sc alloys. Even as the Sc content increases, no improvement in MTF can be noted. The only difference is that the rate of MTF change with annealing is much slower in films with 0.3Sc. As discussed in the previous section, the addition of Sc effectively retards grain growth of the film. Thus, this slower rate of change in MTF and DTF in Al-0.3Sc annealed at 550°C or Al-0.1Sc annealed at 500°C can be attributed simply to the grain size.

When lines were aged before testing, MTF was monotonically decreased with aging time, regardless of Sc content and annealing temperature. The decrease of MTF with aging time was small but it was measurable. For the case of Al-0.3Sc annealed at 550°C for 60 min., subsequent aging treatment at 225°C for 6 and 48 hrs resulted in a decrease of MTF by 17 and 29%, respectively. No clear correlation could be made between the MTF variation and the annealing time and temperature. Although the reason for a decrease of MTF with aging is still not very clear, this result, in conjunction with the results from annealing tests, indicates the addition of Sc was not effective in decreasing the migration of Al.

The Role of Sc on Electromigration

Previous work has reported that the Sc additions enhance reliability of the lines against electromigration as well as stress induced damages such as hillock formation during annealing [3]. It is believed that hillock formation is minimized by preventing grain growth. The present study has brought some further insights on the effect of the Sc additions. As mentioned earlier, Sc is very efficient at retarding grain growth and therefore helps to retain a uniform microstructure which is more resistant to void formation during electromigration. However, we believe that this effect quickly looses its advantages as the line width physically decreases, since grains though small may be large enough to span across the line. This effect is even more pronounced for longer annealing treatments for which secondary grain growth occurs. When this occurs, the grains in the polygranular segment which is bounded by abnormally grown bamboo grains is extremely small. The example of this line structure is shown in Fig.2. In this case, we observed the formation of large hillocks, extruded more than 0.5 μm in height, with substantial frequencies.

It will be informative to compare the role of Sc on EM in Al to that Cu, which is rather well characterized. In order to failure proceed in Al films with Cu, Cu should be swept away at the failure sites. Until the sweeping of Cu is completed, electromigration of Al is suppressed. This mechanism can be easily visualized when test was done at lines with polygranular segment. The sweeping of Cu results in the formation of a large precipitate at the down-stream termination of polygranular segment, after which voiding occurs at the up-stream end [9,10]. When the failure site in Al-Sc interconnects were examined, such a behavior was not observed. Instead, it appeared that Sc is immobile. The typical morphology of failure sites in Al-0.3Sc lines tested after 60 min. annealing at 550°C is shown in Fig.3. Both the TEM and SEM micrographs reveals that failure mechanism is identical to that pure Al, as failure occurred at the up-stream end of polygranular segment, while hillock does appear at the other end. However, there is no sign of Sc sweeping. Besides, precipitates were found both in grains and grain boundaries of polygranular segments without any noticeable sign of redistribution.

The results of this study indicate that Sc does not migrate during current stressing. There are several possibilities for this result. It is possible that the electromigration driving force on Sc

itself is much smaller than that on Al. It is also possible that the Al_3Sc precipitates are too stable to dissolve and to allow Sc to migrate. In either cases, the consequence is the same that there is no kinetics benefits of electromigration from the Sc addition. It seems that beneficial effect of solutes on Al electromigration is somehow related to the ability of preferential migration, like Cu does. In order to confirm this idea, as well as to substantiate the conclusions we made in this study, we are currently performing the same test on Al-0.3Sc alloys with the addition of Cu. The preliminary results so far deepens the analysis we made here in several ways. First, it was found that the addition of Cu on Al-Sc increases the magnitude in MTF at least an order of magnitude. Second, failure site was found to be associated with the sweeping of Cu. Like in the case of Al-Sc, however, the Al-Sc-Cu did not exhibit any sign of Sc sweeping at the failure sites. The details of this investigation will be published in the future.

CONCLUSION

A study on the effect of Sc on the resistance against EM of Al lines was performed. The study attempted to isolate the role of Sc on the grain structure and on the kinetics of Al EM. It was shown that Sc is a very efficient grain refiner and delays the evolution of failure statistics observed in pure Al. Furthermore, the analysis of the EM tests and the characterization of the failure sites seemed to indicate that Sc, as opposed to Cu, does not influence the kinetics of Al migration. It was therefore concluded that Sc may not be an excellent alloying element for enhancing EM reliability in sub-micron lines.

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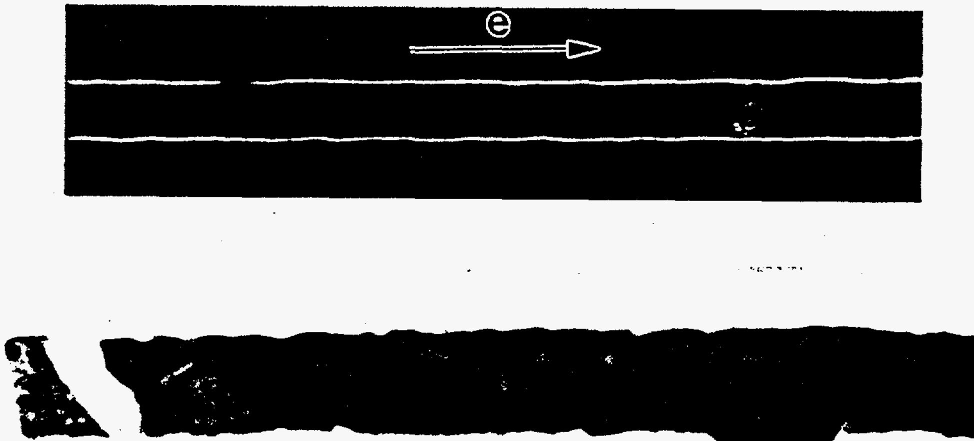

Fig.4 SEM (a) and TEM (b) micrographs showing the typical failure morphology in Al-0.3Sc lines, tested after 60 min. annealing at 550°C.

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