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Electromigration Studies of Al-Intermetallic Structures

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The use of an intermetallic layer in Al conductor lines has been reported to improve the electromigration lifetime. This paper summarizes the results of a metallurgical study of the electromigration behavior of the intermetallic structure. The investigation focused on three fundamental characteristics: the mass transport under a direct current, the microstructure and the distribution of the current density. The improvement in the electromigration lifetime is attributed primarily to improved microstructure of the conductor line and the redundant barrier function of the intermetallic layer.

1. Introduction

As device dimensions continue to reduce in VLSI (very-large-scale integration) technology, the thin film interconnects have to carry increasingly large current density. This gives rise to reliability concern due to electromigration damage in fine lines. Electromigration describes the movement of atoms in a metallic conductor induced by the passage of a direct current.[1] Its magnitude is proportional to the atomic diffusivity (mobility) and the current density (driving force). The formation of electromigration damage, e.g. opens or shorts in the line, requires local flux divergence which can be generated by various types of inhomogeneity in the conductor, such as those from grain size, local heating and stress concentration.

Most of the previous studies have concentrated on conductors wider than 3μ and the subject has been reviewed in Refs. 2, 3 and 4. With trends continuing toward finer lines in VLSI, the character of the electromigration problem has evolved substantially. The nature of this problem has been discussed and two basic aspects were emphasized.[5] The first originates from the high current density which not only imposes a large electromigration driving force, but also enhances the Joule heating problem. Both these factors will increase the mass transport and accelerate the rate of damage formation. The second problem is caused by the reduction in line dimension. Since the formation of electromigration damage requires flux divergence, the nature of the divergent site is an important factor to consider. For standard Al conductors, the grain size is usually about the film thickness, i.e., 0.5 to 1μm. As the linewidth reduces to the micron range, the nature of the effect of grain structure on damage formation will change. For example, the statistical nature of the damage formation process will be different since damage at each individual divergent site, such as a grain boundary junction, can effectively produce a complete opening of the line without a statistical linkage of several divergent sites across the conductor line. Such structural aspects of electromigration will become increasingly important for fine lines. Indeed, a modification which consists of the grain structure of Al conductors into a "bamboo" form has been found to improve the electromigration resistance for fine lines with width in the micron rang.[6]

A different structural modification of incorporating an intermetallic layer in the Al-Cu film has also been found to be effective in improving the electromigration lifetime of 1-2μm lines.[7] The intermetallic layer is prepared by reacting Al with a transition metal, e.g., Ti and Cr at about

400°C to form Al-rich intermetallic compounds, e.g., Al_3Ti and Al_7Cr. Mechanisms responsible for the improvement have been suggested, including reduction in the grain boundary transport and barrier for void formation. This paper reports the results of a metallurgical study of the electromigration behavior of the intermetallic structure. The investigation focused on three fundamental characteristics: the mass transport under a direct current, the microstructure and the distribution of the current density. It is hoped that these studies can provide a better understanding of the electromigration improvement in the intermetallic structures.

2. Results

Samples were prepared using the procedure mentioned in the earlier study.[7] The mass transport was measured by the drift velocity technique which has been used previously by Blech in a study of Al conductors.[8] The drift velocity was measured in 5μm wide fine lines of stripe length varying from 10 to 300 μm, which were deposited on a Ti-W (10%wt. Ti) underlayer. No overcoating was used so that the edge displacement of strip could be measured by scanning electron microscopy (SEM). The time dependence of edge displacement due to electromigration provides a measure of drift velocity. The result indicates that electromigration-induced mass transport of Al-Cu is not significantly reduced due to the presence of the intermetallic layer. Thus, the reduction in electromigration damage is probably not caused by a decrease in the mass transport.

Microstructure studies on the Al-intermetallic structures were carried out by transmission electron microscopy (TEM), using flat-on as well as cross-sectional mode of observation. Flat-on TEM and x-ray diffraction data indicated a <111> preferred orientation of the Al grains. Cross-sectional TEM observations showed that the top and bottom Al layers of 4000Å have uniform line thickness and smooth surfaces. Relatively uniform and columnar grain structure were seen in both Al layers (Fig. 1). Using TEM direct imaging and microdiffraction analysis, we found the formation of a continuous, symmetrical Al-intermetallic middle layer plus the Al_2Cu compound phase particles both in the grain boundaries and near the middle layer interfaces. The Al_2Cu precipitates on the surface of the top Al layer were found to be 0.75μm in average size and uniformly distributed. The overall compound layer structure was further confirmed by Rutherford backscattering and Auger sputter profiling measurements. These studies revealed two microstructural characteristics, both are useful in reducing electromigration damage. First, the relatively uniform columnar grains provide an almost optimum structure for reducing grain boundary divergent sites. Second, the continuous intermetallic layer is effective in blocking the void linkage through the top and the bottom layers. Thus, considerable mass depletion can occur in the top and the bottom layers, but so long as the intermetallic layer remains intact, the whole structure can continue to carry current. This effectively increases the lifetime of the conductor line.

The purpose of the current density calculation is to find the extent of current inhomogeneity due to the presence of the resistive intermetallic layer since inhomogeneous current distribution can give rise to current crowding and consequently damage formation. Finite element analysis was used to calculate the distributions of the electric field, current density in the intermetallic structure. The calculation employed the cosmic NASTRAN computer code.[9] Results were obtained for two as well as three dimensional structures. For typical structures the intermetallic layer has about 10% of the total thickness but ten times the resistivity of the Al layer. A typical result of the distributions of the current density is presented in Fig. 2. It can be seen that the presence of the intermetallic layer has only a small effect on the overall distributions of current density.

3. Summary

Summarizing the results of our study, we found that the incorporation of an intermetallic layer in an Al conductor line does not have a significant effect on the mass transport or the current density distribution in the top and bottom Al layers. The improvement in the electromigration lifetime is attributed primarily to changes in the microstructure which reduce damage formation, as well as to the presence of a redundant barrier which blocks void growth and maintains current continuity.

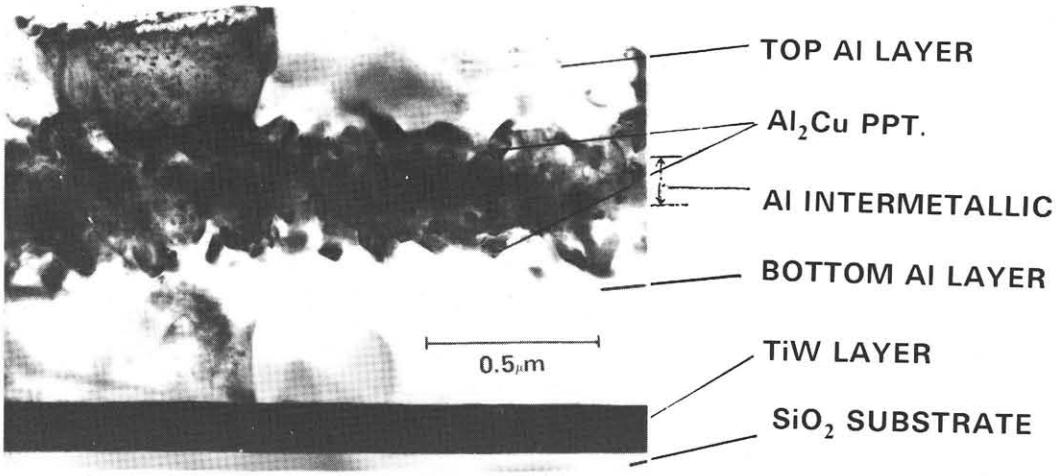

Fig. 1. Cross-sectional TEM micrograph showing the microstructure of an AlCu film with an intermetallic layer.

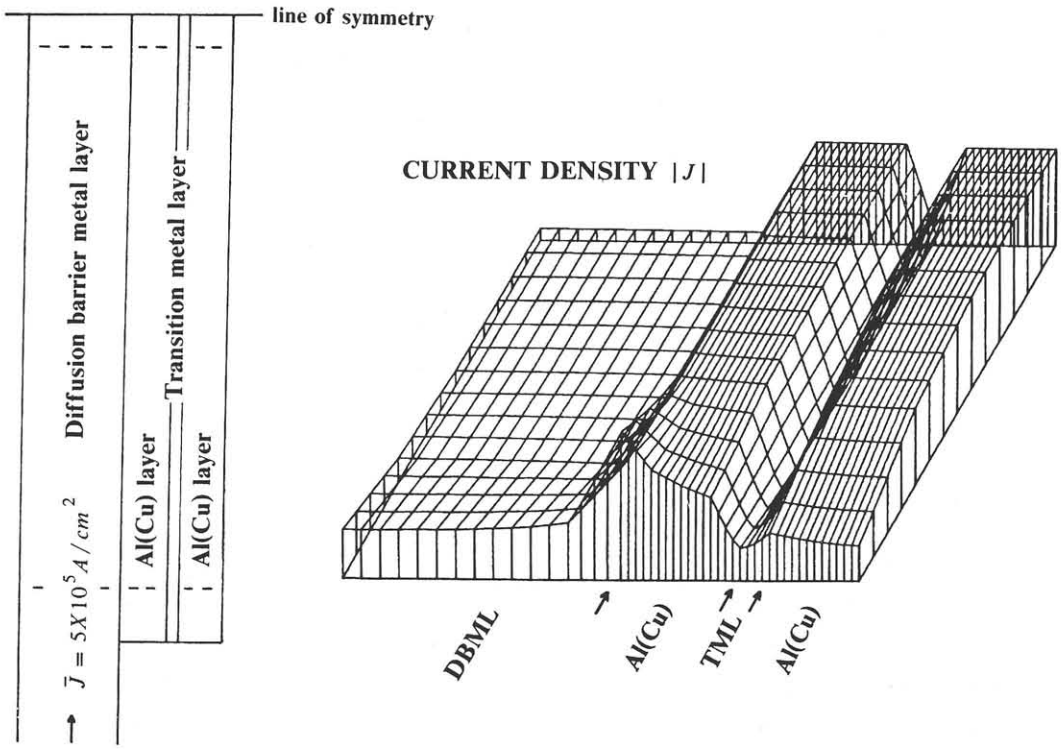

Fig. 2. Schematic drawing of the overall current density distribution in an Al intermetallic test structure. This structure was used to measure the drift velocity and its configuration is also shown.

References

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