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Reduction of Electromigration in Aluminum Films by Copper Doping

Abstract: We have found that the lifetime of aluminum films subjected to high current densities at elevated temperatures can be increased by the addition of copper. Previous studies have indicated that the failure mechanism is a combination of electromigration-induced phenomena, including nucleation and growth of voids, which are gated primarily by material transport along grain boundaries. On the basis of the present study, it appears that the presence of copper causes an appreciable retardation in the rate at which this overall combination of processes takes place, thereby producing a considerable increase in lifetime.

Introduction

Electrical "opens" due to material depletion can occur in thin aluminum films that have been subjected to current flow for extended periods of time. Such a mode of failure has received particular attention during the past few years because of its relevance to thin-aluminum-film conducting stripes, which are in widespread use in planar semiconductor devices and integrated circuits. Thus far, experimental studies[1] have indicated that although the failure ultimately occurs as a result of the catastrophic growth of voids, the initial nucleation and growth stages of the voids are gated primarily by grain-boundary electromigration. Related electromigration effects in bulk aluminum have also been reported.[2] Our observations indicate that the occurrence of such failure can be retarded appreciably by means of copper doping.

Sample preparation

The films used in this study were prepared by vacuum deposition onto thermally oxidized silicon wafers. The deposition system contained a multiple-position rf-heated source, so that both aluminum and copper layers could be deposited within one pump-down cycle.[3] The substrate temperature was maintained at 200°C during film deposition; the ambient pressure was of the order of 10^{-7} Torr. Aluminum deposition, from BN-TiB_2 crucibles of the type described by Ames et al.,[4] was carried out at a rate of about 20 Å/sec. Copper doping was achieved by depositing a 3000-Å-thick aluminum layer, followed by a layer of copper and a second 3000-Å aluminum layer, and subsequently annealing the composite film in N_2 for 20 minutes at 530°C. Control films, the structural properties of which have been described elsewhere,[5] were prepared similarly except that no copper was used.

To facilitate studies at high current densities, the films were photoprocessed into 0.3-mil × 10-mil stripe patterns containing considerably enlarged terminal areas for voltage- and current-lead attachments. The wafer material containing the stripe patterns was diced into 75-mil × 75-mil chips, then bonded to modified TO-5 type headers by means of a conductive epoxy. Electrical contact to the stripes was made through ultrasonically bonded 1-mil-diameter Al wires. A typical stripe prepared in this manner is shown in Fig. 1. Five wires were bonded at each terminal, four for use as current leads and the fifth as a voltage lead.

Accelerated life testing

The resistance of a stripe could thus be obtained under conditions approaching the usual four-terminal manner and the average temperature rise during testing at high current-density levels could be estimated by using the stripe as its own resistance thermometer. (Calculations by Chhabra and Ainslie[6] had indicated that if the temperature rise due to self-heating was small in comparison with the ambient temperature, the stripe could

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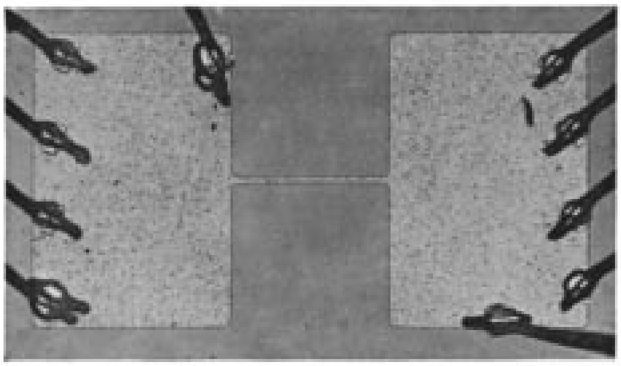
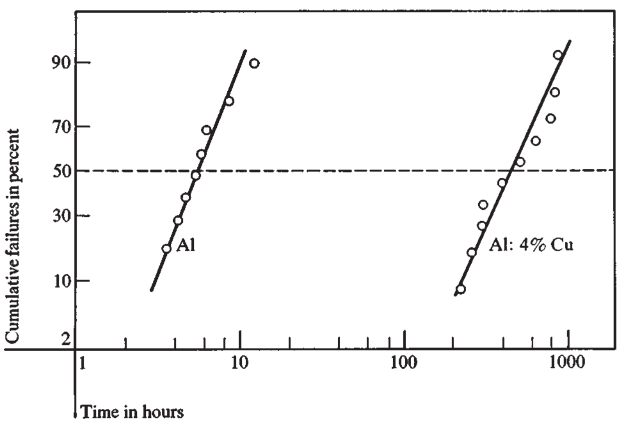


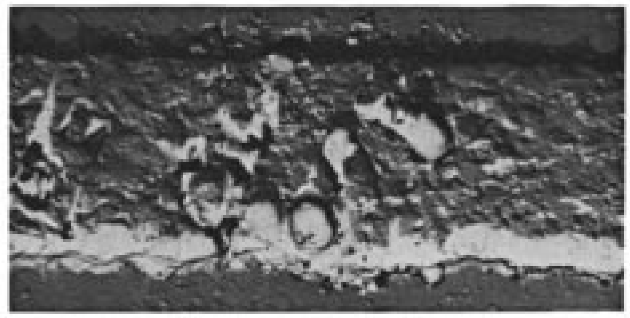
Figure 1 Photograph of 0.3-mil $\times$ 10-mil aluminum stripe showing the extended terminal areas and connecting wires.

Figure 2 Cumulative percentage failure data as a function of failure time for undoped and copper-doped aluminum stripes subjected to a current density of about 4×10^6 A/cm² at a stripe temperature of about 175°C. The ordinate scale is based on a Gaussian probability distribution.

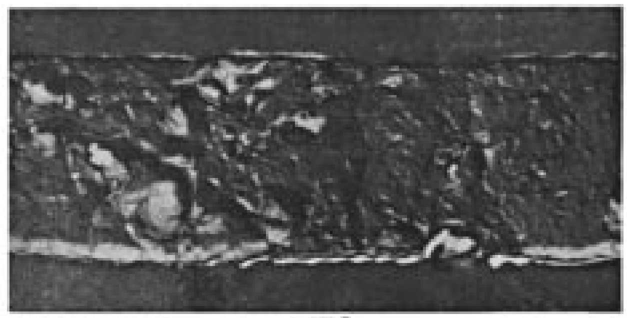


be regarded as having an approximately uniform temperature distribution, except for small gradients at the ends.) To minimize the temperature rise, we used only 1000 Å of thermally grown SiO_2 and a relatively large chip. In addition, the specimens were immersed in silicone oil (Dow-Corning type 705) while being subjected to the high current densities that were used to induce failure. Typically, the temperature rise thus obtained was estimated to be about 10°C at a current density of 4×10^6 A/cm². Stripe temperatures determined during accelerated life testing were considered to be accurate to within ±5°C during most of a typical run. (It was not possible to characterize the temperature of a given stripe just prior to failure because of the difficulty in interpreting the resistance increase that was usually observed at that point in the run.)

Due to the variability in failure time among similarly prepared stripes, it was necessary to determine the



Al



Al: 4% Cu

Figure 3 Electron micrograph replicas of undoped and copper-doped aluminum stripes showing areas in the vicinity of failure points.

normative failure time for each set of conditions by testing groups of stripes and characterizing the results in terms of some minimal statistical procedure. For this purpose, best fits to log-normal distributions were used. (A set of stripes was tested and the cumulative percentage of failures for the stripes in the set was plotted on a Gaussian distribution scale as a function of the logarithm of the time at which each stripe failed.) By minimizing the temperature rise during accelerated testing and by using large terminal areas and several wire-to-film contacts at each terminal, gating by failures in the vicinity of the terminals was avoided.

Experimental results

Typical cumulative percentage failure data are shown in Fig. 2 as a function of time in use for two groups of stripes that were prepared as described and subjected to a current density of about 4×10^6 A/cm² at a temperature of about 175°C. The increased lifetime for those stripes containing approximately 4% copper is clearly evident. For example, the median lifetime for the set of stripes that did not contain copper was about 6 hours, in comparison with 400 hours for the set that contained 4% copper, indicating an improvement-in-lifetime factor of about 70. Additional data, obtained from comparable samples, indicate that the lifetime decreases with decreasing copper content. Furthermore, the data, which have been obtained at current densities down to 1×10^6 A/cm^2 at temperatures of about 175°C, and at temperatures down to 125°C at a current density of 4×10^6 A/cm^2, are consistent with an assumed inverse-third-power dependence of the lifetime on the current density and a dependence on temperature that is governed by an activation energy of about 0.5 to 0.7 eV, in accord with values obtained for undoped stripes.

Electron micrograph replicas of regions in the vicinity of the failure point are shown in Fig. 3 for representative stripes in the control and copper-doped groups from which the results shown in Fig. 2 were obtained. Study of these replicas suggests that failure occurred as a result of the formation of a fine interconnected network of crevices, which may be associated with preferential nucleation and void formation in the vicinity of grain boundaries as reported by previous experimenters.[1] Hillocks are also seen in the vicinity of the region of failure, a further indication that mass transport has taken place.

Conclusions

The addition of copper to aluminum thin-film stripes has been found to achieve a considerable increase in lifetime. Typically, an increase by a factor of 70 was achieved at a current density of about 4×10^6 A/cm^2 and a stripe temperature of about 175°C through the addition of 4% copper.

Although a much longer time was needed to induce failure in the copper-doped stripes than in the undoped stripes, the appearance of the regions of failure in each is similar. This suggests that the same failure processes are operative for the undoped and doped stripes and, therefore, that the copper doping acts mainly to markedly retard the failure process rather than to alter its intrinsic nature.

Acknowledgments

The authors thank D. Dong, H. Luhn, V. Ranieri, W. Schug and other members of the Research Center staff for their technical assistance in sample preparation and testing, and C. Aliotta for obtaining the electron micrographs. They also acknowledge the contributions made through numerous conversations by various members of the IBM Components Division in East Fishkill, New York.

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Received August 28, 1969; revised, January 15, 1970

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