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# INTEGRATED CIRCUITS INTERCONNECT METALLIZATION FOR THE SUBMICRON AGE

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**ABSTRACT**

The interconnect metallization being used by the semiconductor industry has been aluminum or aluminum silicon. Aluminum silicon is being replaced by aluminum copper and aluminum copper silicon, due to its superior resistance to electromigration and hillock growth. This paper discusses the implementation of aluminum copper/silicon alloys in semiconductor processing, along with a review of the problems and advantages of the same.

## INTRODUCTION

Aluminum has been used for a long time in the IC processing industry as an interconnect metal due to its cost and electrical properties. Tighter geometries and shrinking device sizes have led to increased current densities and multilevel capability requirement for interconnects. Keeping in view the above points, it is essential that factors such as: 1) electromigration, hillock growth (Herman *et al.*, 1972; Rey *et al.*, 1984) and 2) corrosion be considered for submicron geometries.

## ELECTROMIGRATION, HILLOCK GROWTH

A number of studies (Weaver and Parkinson, 1971; Vandenberg and Hamm, 1981; Shih and Ficalora, 1981) has been done related to the dynamics of gold-aluminum intermetallic formation. This intermetallic formation subsequently leads to the phenomenon known as purple plague and Kirkendall voiding (Clifford *et al.*, 1974; Philofsky, 1970) resulting in weaker bonds causing electrical and mechanical failures. The mechanism of Al-Au interdiffusion is presented (Baglin, 1978).

Copper has been added to aluminum for a long time to reduce electromigration and the occurrence of failure due to stress induced voiding (Ames *et al.*, 1970). The void formation process is reduced due to the formation of the theta phase-$Al_2Cu$ (Berenbaum and Rosenberg, 1971). Hence, the failure mechanism has been summarized as being mainly due to grain boundary electromigration which consists of nucleation and growth of voids. The table from d'Heurle and Ho (1978) shows how the addition of copper can dramatically increase the median time to failure. The addition of copper is known to inhibit grain boundary movement by a pinning mechanism (Herman *et al.*, 1972) where second phase particles in Al retard creep of the parent phase and therefore inhibit growth of annealing hillocks (Philofsky *et al.*, 1971).

## IC PROCESSING AND CORROSION MECHANICS

The above advantages of the addition of copper are offset by certain disadvantages, the most important of which is corrosion. Al-Cu films especially have been found to be more susceptible to intergranular and pitting corrosion than pure Al (Totta, 1976). The prime source of corrosion was found to be chlorinated hydrocarbons which had decomposed in wafer cleaning baths. From corrosion studies on Al-Cu bonding pads, it was understood that the formation of $Al_2Cu$ particles in Al-Cu was believed to be formed at the grain boundaries and this formation resulted in the film being depleted of Cu in the vicinity of the particle. This formed a shorted galvanic cell where the electrode potentials are reported to be $-0.85$ volts for Al and $-0.73$ volts $Al_2Cu$. The $Al_2Cu$ acted as a cathode in contact with the aluminum which acted as an anode. In the presence of a suitable electrolyte, corrosion can occur. The corrosion of aluminum proceeds around the $Al_2Cu$ particle until the aluminum is deposited and the $Al_2Cu$ particle is electrically isolated (pit). The corrosion rate is dependent on the size and homogeneity of distribution of the particle. The corrosion product is believed to be $Al(OH)_3$. In the presence of moisture, this forms a thin fluid which spreads over the metal surface around the pit. As the fluid dries up it forms a hard film which causes poor adhesion of the gold to the Al-Cu contact pad. It is noted that the distribution of copper is of critical importance and, thus, the homogeneity of $Al_2Cu$ is a factor to be considered in the film processing (Thomas and Berg, 1985).

Corrosion also occurs during the etching of Al-Cu/AL-Cu-Si films. This is due to the fact that Cu forms CuCl with chlorine which in itself is relatively non-volatile below 175°C. Thus, Cu residues remain after these alloy films are dry etched. This makes Al-Cu more difficult to etch in chlorine plasmas. As the Cu concentration goes up, etching becomes a bigger problem (Wolf and Tauber, 1986) along with the problems associated with nonhomogenity which leads to the formation of an electrochemical potential (Pramonik and Saxena, 1983).

Corrosion modeling has been done wherein corrosion activity is determined from the resistance rise of the corroded Al-Alloy region. It was shown that corrosion activity decreases as a function of time (Fan and McPherson, 1988). To counter this problem, the substrate temperature was increased to promote CuCl desorption and ionic bombardment of the surface is increased so that significant sputtering of residue occurred. Corrosion due to the galvanic cell effect takes over in the presence of moisture, which reacts with the chlorine residues forming HCl, which in turn plays the role of an electrolyte. Wolf and Tauber (1986) showed weight gain versus exposure time. It was clearly seen that with no Cu there was a negligible weight gain, where weight gain indicates the extent of corrosion. With Cu concentration greater than 1%, there was a significant weight gain change indicating increased corrosion activity. Using $CF_4$ right after the $Cl_2$ plasma etch is believed to replace the chemisorbed chlorine with flourine, thus passivating the aluminum by the formation of nonhydroscopic $AlF_3$. Using $CHF_3$ on the other hand, is thought to deposit a polymer film over the Al, thereby sealing the surface (Wolf and Tauber, 1986). The impact of a post etch *in situ* with $CHF_3$ plasma passivation has been discussed (Fan and McPherson, 1988). It also is noted that thermal oxidation at 300°-350°C and 1 atm oxygen pressure for greater than 30-45 minutes was found to be effective in improving the corrosion resistance of the etched sample (Lee and Eldridge, 1981). Ritchie and Andrews (1981) state that the $CF_4/O_2$ plasma which may be used for passivation could cause corrosion. It was observed that two possible phenomena could be responsible. One was that Al is corroded spontaneously due to cathodic corrosion in the presence of electrolytic fluoride contamination (Comizolli, 1980) and secondly, it was reported that modification of the native aluminum oxide and change in its electrochemical behavior is possible due to the introduction of fluoride ions (Valand and Nilsson, 1977).

Hence, it was suggested that the plasma exposure time be increased so that chemisorpotion of oxygen will take place on the pads which would in turn block the reactive sites, thus retarding corrosion (Flamm, 1979).

The above discussion on corrosion has been deemed important since it has a direct relationship to bonding and reliability. It is critical that great care be taken during processing of integrated circuits. Delays in transferring lots from one process to another, especially after etching, should be avoided.



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Precipitation influence on electromigration in Al-Cu thin films has been studied (Walker and Goldsmith, 1973) and it was concluded that the total homogeneous distribution of copper atoms in the films controlled the effective lifetime of the film. d'Heurle and Ho (1978) observed that failures of Al-Cu or Al-Cu-Si occurred in areas of the conductor that are depleted of Cu and in areas in the vicinity of large $Al_2Cu$ precipitates. Formation of second phase particles have been studied in Al-Cu films (Mader and Herd, 1972), and it was observed that the film surfaces provided preferential nucleation sites for the equilibrium precipitate of theta-$Al_2Cu$.

## GOLD BONDING TO Al/Al-ALLOY

A number of papers have discussed bonding methods for improving bonding integrity of Au to Al (Hund and Plunkett, 1986). Ball-bond integrity tests have been discussed (Harman, 1983). A bond failure mechanism for Al-Si was studied with the conclusion that silicon nodules formed resulted in points of high stress during bonding. A pad structure with Ti:W below Al-1%Si acted as a buffer to stress, which helped reduce cratering created by silicon nodules in the pad structure (Ching and Schroen, 1988). Removal of the deposited PSG layer from the pad structure decreased the susceptibility of the pad to cracking induced by the silicon nodules (Koch *et al.*, 1986). Also available are papers on effects of molding materials on Au-Al bonding (Khan *et al.*, 1988; Richie and Andrews, 1981).

It is the authors' understanding, after discussions and review of literature, that if fluorocarbons are used in the processing steps, it is desirable to expose with oxygen long enough for the oxygen to react with the Al-Cu contact pad and form a passivating layer, thus, preventing fluoride ions from corroding the metal.

## METHODOLOGY FOR STUDIES OF BOND INTEGRITY

Bonding window studies of thermosonic wire bonding have been made with reference to Al; Al-Cu; Al-Si; and Al-Cu-Si systems. This method has been suggested as a powerful tool in conjunction with wire pull and ball shear testing for bonding studies (Berg and Mitchell, 1985). The criterion used was by visually inspecting sticking vs. nonsticking bonds. it was ascertained by using this criterion that a large fraction of the very weak bonds were identified. The thickness of Al; Al-1%Si; Al-1.5%Cu; Al-1%Si-1.5%Cu in this study was 1.2 micrometers. Six ultrasonic powers and three bonding times were evaluated. The ultrasonic powers and times were chosen to give many nonsticking bonds at low power-time combinations and many sticking bonds at the highest settings. The bonding windows are shown in Figure 5 of Berg and Mitchell (1985). It is clear that the bonding windows are sensitive to the change in metallization. Also presented in Figure 12 of Berg and Mitchell (1985), are bonding parameters data which showed percent nonsticking bonds vs. first bond force for Al-1.5%Cu metal. The best bond force is found to be 35g.

Other methods of improving gold ball bond reliability and testing are presented by Hund and Plunkett (1986).

## CONCLUSION

The advantages involved in the use of Al/Cu/Si alloys offset its disadvantages. Copper concentration and also silicon concentration should be closely controlled with copper concentration kept below 4%. High silicon concentration can cause precipitation of silicon nodules contributing towards bond integrity degradation.

In conclusion, as long as the composition is well balanced, which depends on the need, Al-Cu/Si will be the interconnect metallization of the future submicron era.

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