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REDUCED ALUMINIUM ELECTROMIGRATION IN FUTURE INTEGRATED CIRCUITS – A PROBLEM OF TEST PROCEDURE AND THRESHOLD MECHANISMS*

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In aluminium interconnect lines of integrated circuits there are different electromigration failure modes such as stripe interruptions and contact failures. For the conditions demonstrated here, the electromigration drift velocity limits the lifetime of metallization by contact failure long before interruptions would occur. In short aluminium lines, as well as in all Al–Cu lines, the mass flow is reduced by a grain boundary electromigration threshold. Considering different threshold mechanisms, grain boundary and interface electromigration can be eliminated in large-grained narrow lines. The remaining, drastically reduced bulk electromigration will not be detectable under operating conditions.

1. INTRODUCTION

Electromigration in metal interconnect lines is a limiting factor for the reliability of future integrated circuits. Aluminium is widely used as the basic material for IC metallization, but the inherent problem is the electromigration sensitivity which increases with current density, thus emphasizing the reliability problem of future metallizations.

In order to investigate the electromigration behaviour, accelerated lifetime tests are performed using increased current densities j and elevated temperatures T. Generally, the measured data have been stripe interruption failure times of continuous interconnect lines which end on bonding pads. To get reliability data for integrated circuits, test results are transformed to operating conditions by applying the empirical formula for the median time to failure $t_{50} \approx j^{-n}\exp(E_a/kT)$. In this formula E_a is the activation energy for stripe interruptions which depends on fabrication[1] and test conditions[2]. The exponent n of the current density covers a wide range. Values between about 1.5 and 13 have been measured[3,4]. Generally[5], n does not equal 2.

If the operation conditions of integrated circuits are, for example, current

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densities of 2×10^5 A cm^{-2} at 90 °C, the estimation of operating failure times t_{50} would yield about 40 years for 1.8 μm wide, annealed and oxide-covered aluminium lines[6] ($E_a \approx 0.55$ eV, $n \approx 3$). These failure times can be further improved by adding copper[7], vanadium or chromium[8], or by using multilayers like Al–Ti–Al[7]. However, the questions of whether stripe interruptions always limit the reliability of practical metallization and how reliability can be improved for future increasing current densities in integrated circuits now arise.

2. CONTACT FAILURE BY MASS DEPLETION

An electromigration failure mode, which should be considered, comes from an almost homogeneous aluminium mass flow which exposes device contacts at the negatively biased ends of interconnect lines in integrated circuits. The mass flow can be measured with moderate current densities—less than 8×10^5 A cm^{-2} in uncovered lines[9]. The test structure for measuring the mass flow J or the aluminium drift velocity v may be a long aluminium line which is connected by two TiN leads to bonding pads. The aluminium line takes over the total current, which is impressed into the TiN, and electromigration causes a drift of the cathode-connected aluminium stripe end[10,11]. A stressed test vehicle is shown in Fig. 1, where aluminium had been transported from the negatively biased stripe end through the unchanged central region to the positive end of the stripe. The drift velocity, which is evaluated by the averaged edge displacement per stress time, is described by the formula[12]

$$\frac{J}{N} = v = j\rho e Z^* \frac{D_0}{kT} \exp\left(-\frac{E_g}{kT}\right) \tag{1}$$

where N is the density of metal ions, ρ the resistivity, eZ^* the effective ion charge, D_0 the pre-exponential factor of the diffusion constant and E_g the grain boundary activation energy provided the aluminium grain size is much smaller than the stripe width. E_g has been measured to be about 0.45 eV[10].

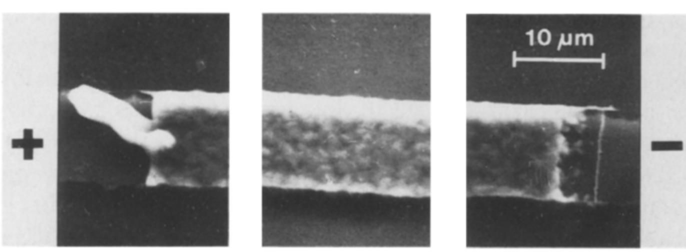


Fig. 1. Negative end, central region and positive end of a long aluminium line connected to TiN leads; $T = 240$ °C, $j = 3.6 \times 10^5$ A cm^{-2}.

From the temperature dependence of the drift velocity, the contact failure times can be estimated for the above mentioned operating conditions (2×10^5 A cm^{-2}, 90 °C). The data in Fig. 2 indicate that a contact of length 3 μm at the end of a straight and homogeneous aluminium line would fail within 1 year by mass

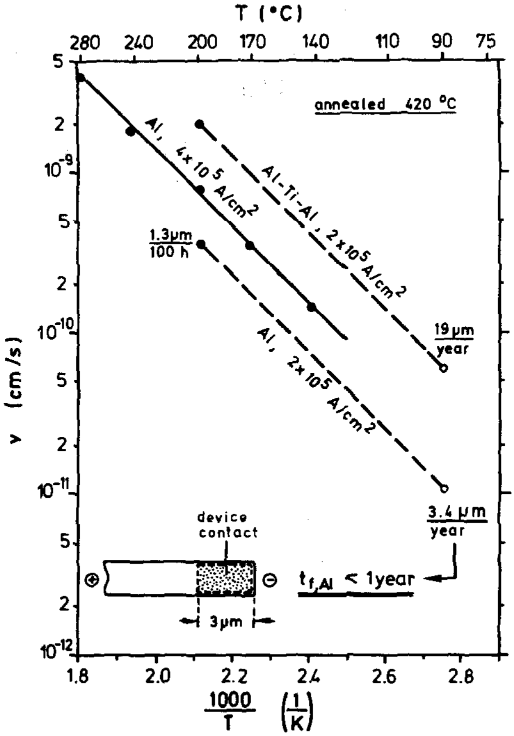


Fig. 2. Temperature dependence of drift velocities v. The contact failure time t_f is given by mass depletion on the contact area, and t_f is equally valid for oxide–covered lines which, for example, end on bonding pads.

depletion, and the comparable failure time of Al–Ti–Al multilayers[7] would be about 2 months, in spite of the extremely long interruption failure times.

In comparison with stripe interruptions, it is obvious that these contacts fail long before interruptions occur, and in those cases it makes no sense to measure interruption failure times.

3. GRAIN BOUNDARY THRESHOLD

The above mentioned failure times are valid only for long lines. When shortening the length l of the stripes, the mass flow is reduced due to a grain boundary threshold for electromigration[11,12], which is given by the product $(jl)_{th}$. Mass flow will become zero if the applied current density is less than a threshold current density being inversely proportional to the stripe length or if the stripe length is shorter than a threshold length being inversely proportional to the applied current density. Below the threshold, reverse gradients compensate electromigration, and above the threshold, these gradients remain constant, thus reducing the total mass flow. Consequently, the current density j in eqn. (1) has to be replaced by $(j-j_{th})$ for $j \geqslant j_{th}$.

The temperature dependence of the worst case static threshold values, which are smaller than the dynamic ones[12], is shown in Fig. 3 for uncovered and SiO_2 covered, annealed lines. For the operating conditions of integrated circuits (2×10^5 A cm^{-2}, 90 °C) the static threshold amounts to 1900 A cm^{-1}. This means that an aluminium line of length 95 μm is not affected by electromigration. If the stripe is longer than this threshold length l_{th}, the electromigration mass flow of eqn. (1) is reduced by the factor $(1 - l_{th}/l)$.

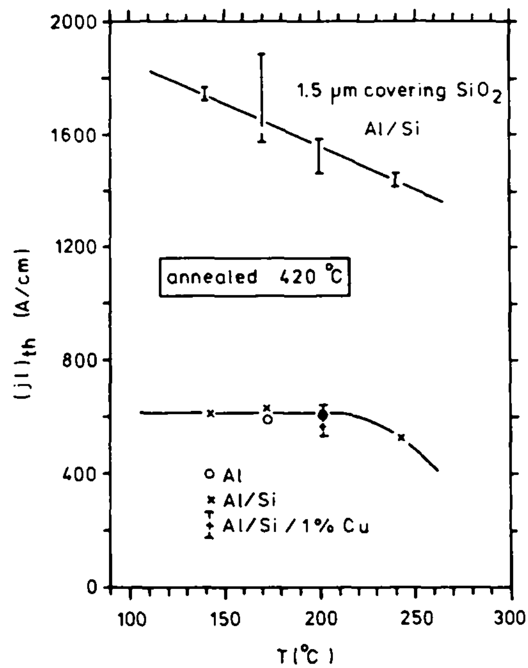


Fig. 3. Threshold value *vs.* test temperature for uncovered and covered samples.

The grain boundary threshold is beneficial for the reliability of integrated circuits, especially as copper is added to the aluminium. Copper blocks the aluminium grain boundaries. Only if copper is drifted out of a stripe length, which is longer than l_{th}, can a reduced aluminium grain boundary mass flow start in the copper-free region[7]. On account of this behaviour the mass flow is non-linear and is drastically reduced as compared with pure aluminium[7] (Fig. 4). The contact failure times by mass depletion of Al–Cu are mainly defined by the copper electromigration preceding the aluminium grain boundary mass flow. That is why the copper activation energy of about 0.7 eV[13] has to be considered when estimating operating failure behaviour. From the failure times in Fig. 4 it may be concluded that Al–Cu is an appropriate compound for current densities exceeding 4×10^5 A cm^{-2} in future integrated circuits.

A much more effective method for reducing the total mass flow might be a change of the active electromigration mechanism. However, first of all it must be known what mechanisms actually exist.

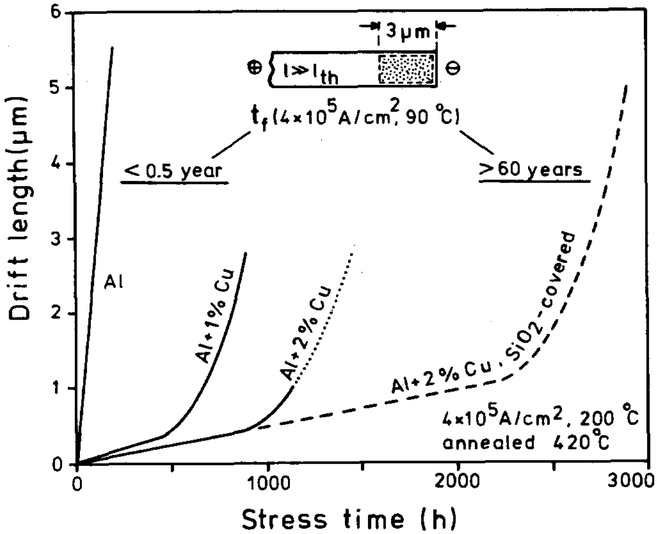


Fig. 4. Drifted length (edge displacement) *vs.* stress time of Al–Cu. The dashed line was estimated by combining test results of uncovered Al–Cu and the static threshold value of SiO_2 covered samples.

4. ELECTROMIGRATION MECHANISMS

Grain boundary electromigration had been identified by local mass accumulation in large-grained aluminium lines on continuous TiN[14]. To find the next mechanism, grain boundary mass flow has to be suppressed by blocking the grain boundary diffusion paths. Therefore, the average grain size should be larger than the

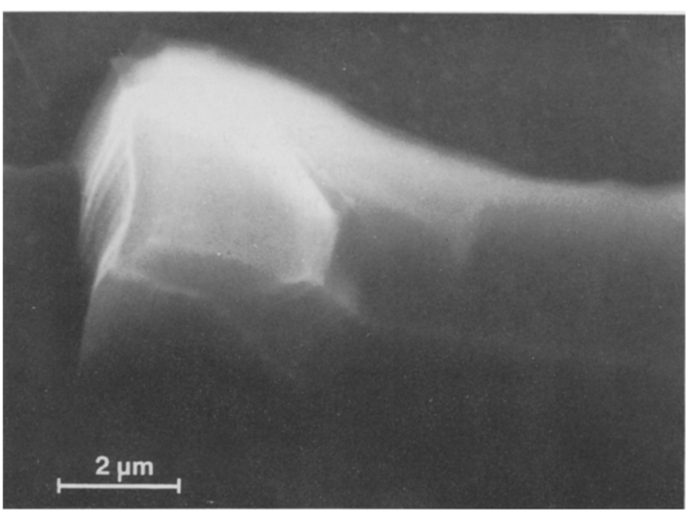


Fig. 5. Positive-biased end of an aluminium line on continuous TiN. The original aluminium end is lifted up by a regular aluminium wedge, which was formed by electromigration along the Al–TiN interface. Test conditions: 192 h, 4×10^5 A cm^{-2}, 200 °C.

stripe width and the test current density should be low. A stressed sample is shown in Fig. 5, showing mass accumulation by interface electromigration[14]. The mass flow of this mechanism can surpass grain boundary mass flow, as was found in Al–Ti–Al multilayers (Fig. 2).

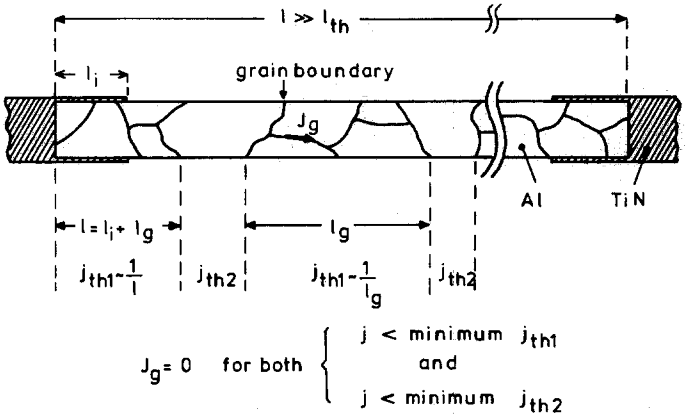
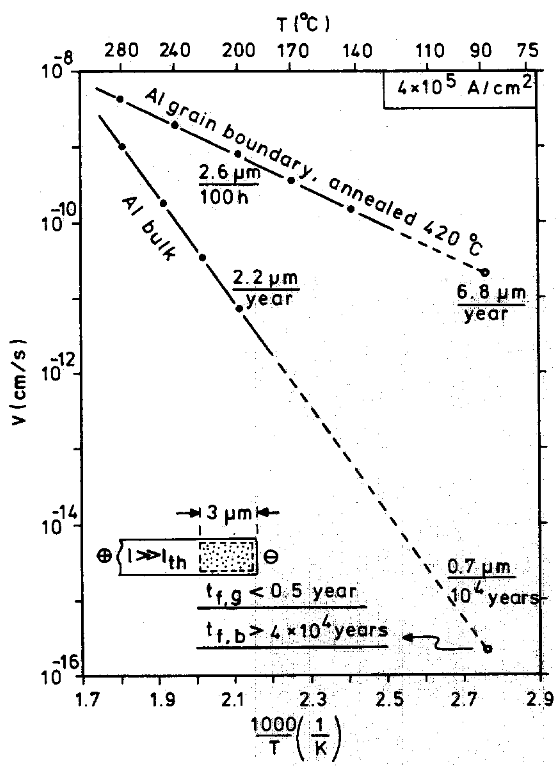


Fig. 6. Test structure for eliminating grain boundary and interface electromigration.



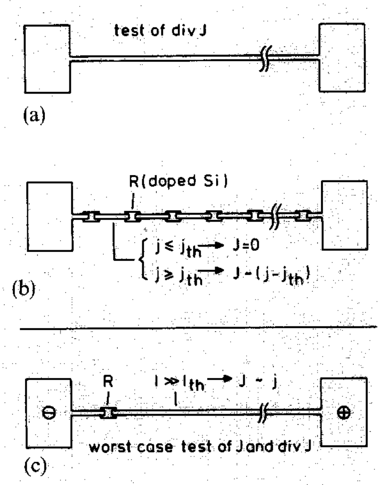


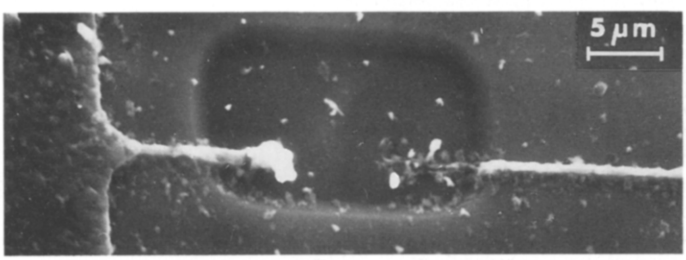
Fig. 7. Temperature dependence of bulk drift velocity in comparison with grain boundary mass flow.

Fig. 8. Different kinds of electromigration test structures without auxiliary layers like TiN (see text). For reliability investigations structure (c) has to be applied.

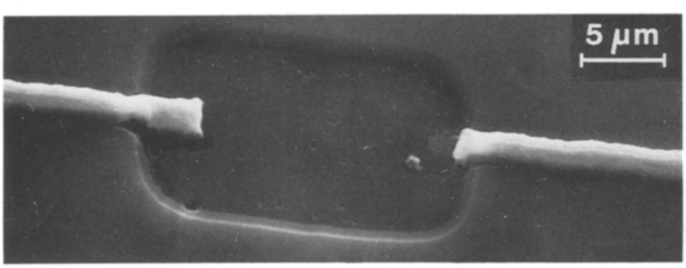
The test structure for the mechanism has to be designed thoroughly (Fig. 6). First, the Al–TiN interface has to be interrupted. Secondly, the interface and grain boundary threshold value has to be considered[14] (j_{th1} in Fig. 6), and thirdly, the threshold of a mass flow mechanism, which bridges single blocking grains (j_{th2} in Fig. 6) must also be taken into account. The value of j_{th2} depends on different parameters and needs further investigations. The lowest value of all j_{th1} and j_{th2} along the aluminium line determines the maximum permitted current density. The drift velocity is drastically reduced in those test vehicles. That is why the test conditions of lines of width 1.2 μm were, for example, about 1 year at 200 °C with 6×10^5 A cm^{-2}. The mass flow mechanism proved to be aluminium bulk electromigration[14], which was confirmed by the activation energy of 1.38 eV[9]. From the temperature dependence of measured bulk drift velocities it may be concluded that contact failure times at 90 °C are increased by a factor of about 10^5 as compared with aluminium grain boundary electromigration (Fig. 7).

5. BULK ELECTROMIGRATION

Apart from the test vehicles, which use TiN leads, bulk electromigration has to be investigated with regard to practical applications. Different test structures may be used (as shown in Fig. 8). Structure (a) only permits stripe interruption tests. Structure (b) contains chains of semiconductor resistors, which are connected by short aluminium lines. In those lines the mass flow is reduced due to the electromigration threshold. The "worst case" of electromigration behaviour in



(a)



(b)

Fig. 9. Bulk electromigration contact failures on a diffused silicon resistor, test conditions were 8×10^5 A cm^{-2} at 200 °C: (a) uncovered Al–Si; (b) SiO_2 covered aluminium (with a molybdenum diffusion barrier layer between silicon and aluminium) after etching the SiO_2 covering. Bulk electromigration threshold suppressed mass accumulation on the left contact.

integrated circuits has to be investigated. This can be done by using structure (c). This test pattern permits the simultaneous evaluation of contact as well as interruption failure times, independent of the prevailing electromigration mechanism[9].

Structure (c), with a highly doped silicon resistor, had been chosen for bulk electromigration reliability tests. Fig. 9(a) shows a typical failure of an uncovered Al–Si line after 13 100 h at 200 °C with 8×10^5 A cm^{-2}. The right contact failed after complete mass depletion by bulk electromigration, while the left contact is characterized by an identical mass accumulation. The aluminium outside the contact regions remained free of noticeable defects.

The aluminium line in Fig. 9(b) was oxide-covered during the test. The contact failure is comparable to Fig. 9(a), but the left contact is free of mass accumulation. The reason is an extremely high bulk threshold value for completely oxide covered lines[15]. This means that most interconnect lines in integrated circuits would never change by bulk electromigration, even if the current density would surpass 1×10^6 A cm^{-2}, and the reduced bulk mass flow in the other lines, which, for example, are ending on positive-biased bonding pads, will not be detectable under practical applications (Fig. 7).

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