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Electromigration Resistance Measurements of Multilayered Interconnections by Short Test Lines

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The electromigration reliability of multilayered interconnections seems higher as longer lines are tested, when estimated in a low failure percentage region. As the test line length becomes shorter, the cumulative failure plot of the electromigration lifetime test deviates more from the usual two-parameter log-normal distribution, and an incubation time is needed as a third parameter to fit the plots to an ideal curve. Because no failures are caused by current stress during the

I. Introduction

Cumulative failure distributions have been analyzed on many kinds of Al interconnections, regarding electro-migration performance[1,2]. Many studies on monolayered interconnections have used the opening of the conductor as the definition of failure. The opening criterion is, however, not suitable for multilayered interconnections, because refractory metal layers are not susceptible to electromigration. For multilayered ones, a percentage resistance increase is adopted as the definition of failures[3]. The failure distributions of multilayered interconnections may not fit log-normal distributions, because their failure definition is completely different from that of monolayered interconnections in which failures have been considered to be distributed according to log-normal distributions.

Hinode and Homma[4] stressed the existence of an incubation time, which corresponds to the third parameter of the modified log-normal distribution, in electro-migration lifetime tests on multilayered interconnections. Other studies have also tried to analyze the results of lifetime tests, according to the modified log-normal distribution with an incubation time, on either mono-layered or multilayered interconnections[5,6].

The purpose of this study was to present a modified electromigration lifetime test procedure to confirm occurrence of the incubation time in the electromigration failure distribution on multilayered interconnections. The incubation time was estimated according to the modified log-normal distribution, using results of a large sample size electromigration lifetime test.

II. Theoretical Background

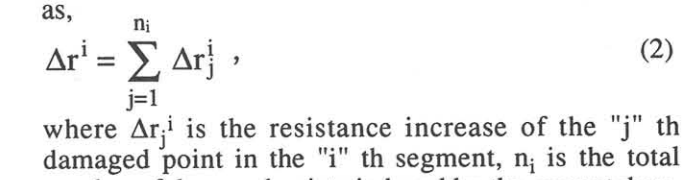
In the multilayered interconnection, the lifetime is defined by the current duration time until the relative resistance increase of the interconnection reaches a definite percentage compared to the initial value. The circuit model of the interconnection is shown in Figure 1. The inter-connection of length L is regarded as a series of segmental interconnections of length l, and the initial resistance value of the test interconnection R_0 is

$$R_0 = \sum_{i=1}^{N} r_0^i = N \cdot \sum_{i=1}^{N} \frac{r_0^i}{N} = N \cdot \langle r_0^i \rangle = r_0 \cdot N, \qquad (1)$$

where r_0^i is the initial resistance of the "i" th segment, N is the total number of the segments in one test interconnection, and r_0 is defined as the average value of r_0^i. The resistance of each segment increases due to current stress during the electromigration lifetime test, and the resistance increase of the "i" th segment Δr^i is expressed as,

$$\Delta r^i = \sum_{j=1}^{n_i} \Delta r_j^i \,, \qquad (2)$$

where Δr_j^i is the resistance increase of the "j" th damaged point in the "i" th segment, n_i is the total number of damaged points induced by the current dura-



L : length of the test interconnection
l : length of the segments
N : total number of segments in the interconnection
Δr_j^i : resistance increase by individual damage
Δr^i : resistance increase of "i" th segment

Fig. 1 Circuit model of the damaged interconnection.

tion in the "i" th segment. Consequently, the total increase of one whole interconnection ΔR can be written

$$\Delta R = \sum_{i=1}^{N} \Delta r^i = \sum_{i=1}^{N} \sum_{j=1}^{n_i} \Delta r_j^i \ . \quad (3)$$

From eqs. (1) and (3), the relative resistance increase of the whole line $\Delta R/R_0$ is

$$\Delta R/R_0 = \sum_{i=1}^{N} \Delta r^i/(r_0 \cdot N) = \frac{1}{N} \sum_{i=1}^{N} \frac{\Delta r^i}{r_0} = \left\langle \frac{\Delta r^i}{r_0} \right\rangle . \quad (4)$$

As a result, $\Delta R/R_0$ is the average value of $\Delta r^i/r_0$. This model is completely different from the "weakest link expression" usually adopted for monolayered interconnections[6]

$$F_L(t)=1-(1-F_l(t))^N, \quad (5)$$

where $F_L(t)$ and $F_l(t)$ are the respective probabilities that a whole interconnection and an individual segment will fail by time t. According to the present model, the whole line is alive even after the failure of the weakest segment because of the averaging effect of the series resistances mentioned above. Elongating the test interconnection length means averaging the relative resistance increases $\Delta r^i/r_0$ on larger number segments of length l and decreasing the dispersion of the resistance increases $\Delta R/R_0$ of a whole line.

When the resistance increases $\Delta R/R_0$ have a small dispersion, the lifetimes of the interconnections, which are defined as current duration times until the resistance increases of the interconnections reach a given value, also have a small dispersion. Because the dispersion of the lifetimes of the interconnections corresponds to the gradient of the cumulative failure density curve on a log-normal plot, the gradients of the curves differ depending on the interconnection length.

When a cumulative failure density curve on a log-normal plot is well fitted by a straight line, many researchers have extrapolated this line towards the lower percentage region which is the important area for evaluating interconnection reliability. A larger percentage failure and lower reliability is expected from the extrapolated line of a smaller gradient cumulative failure curve. The gradient value becomes smaller as the interconnection length becomes shorter, because the dispersion of the relative resistance increase $\Delta R/R_0$ becomes larger as the interconnection length becomes shorter. The reliability of the interconnection is, therefore, lowered by shortening the line length. Consequently, the reliability test results of long interconnections cannot guarantee the reliability of shorter lines than test samples.

However, it is not reasonable to evaluate the reliability of a shorter interconnection from to the extrapolated line of the cumulative failure curve, the gradient of which is determined by the averaging effect of the interconnection resistances. The shortcoming in the prediction is extrapolation of the cumulative failure density curve as a straight line towards the lower percentage region. A certain period is needed for multi-layered interconnections to produce damaged points and to grow voids having large enough resistance increases, because the refractory metal layers become the current bypass region in void areas and retard the resistance increase. Consequently, there should be an incubation time during which no failure occurs. Because there are no failures caused by current stress during the incubation time, it can become a measure of the reliability for electromigration induced failures. The cumulative failure density curve should rise steeply after this incubation time. As the gradient of the cumulative failure density curve becomes smaller, the discontinuity of the curve becomes clearer between the steeply rising region near the end of the incubation time and the small gradient region long after the incubation time, and the incubation time can be found more easily. In order to decrease the gradient of the cumulative failure density curve, shortening the sample line length is effective.

III. Experimental

A 2.5μm wide, 2000μm long straight line was used as the test pattern. The interconnections had a bilayered structure with a 150nm thick W bottom layer and a 400nm thick Al-1%Si-0.5%Cu alloy top layer. Thesamples were annealed at 450°C for 30 minutes in a nitrogen atmosphere, and mounted on ceramic packages. These samples were subjected to a continuous DC current density of 6×10^6 A/cm^2 at an ambient temperature of 120°C.

In order to shorten the sample line length efficiently, the 2000μm long line was divided into 10 short lines by voltage monitoring terminals spaced at 200μm

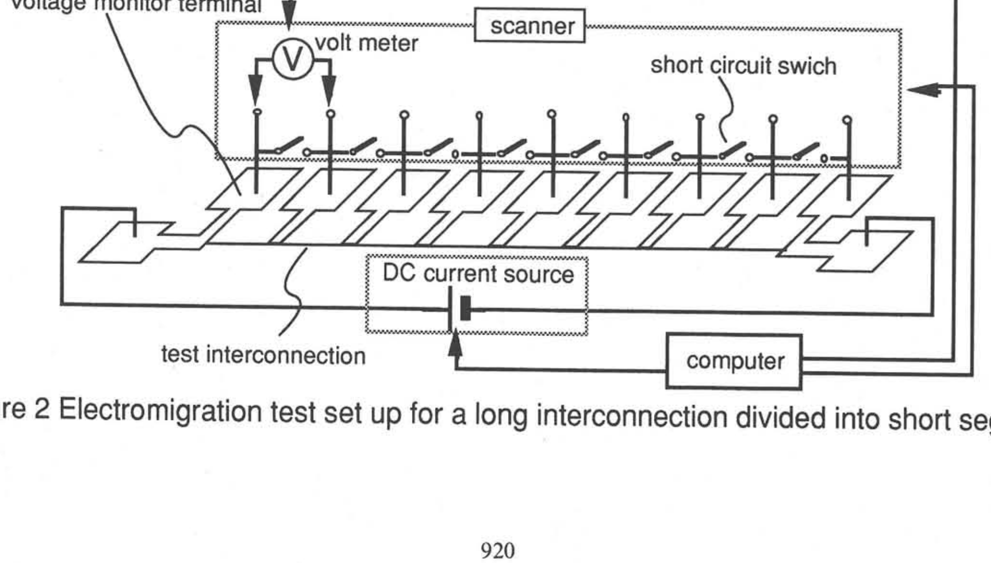


Figure 2 Electromigration test set up for a long interconnection divided into short segments.

intervals. The test set up is shown in Figure 2. A constant current was applied to the 2000μm long line from a current source, and voltage differences between each terminal were monitored to obtain the resistance values between them at constant time intervals. Short circuit paths between each terminal were set up parallel to the interconnection as shown in Fig.2. These short circuit paths were closed when the resistances between the terminals were too large, in order to prevent the current source from overloading. With this bypass mechanism, all 200μm segments could be tested, even after some segments were broken.

IV. Results and Discussion

Figure 3 is the log-normal plot of the cumulative failure distribution for the test interconnections. The lines curved noticeably, and could not be fitted to a usual two-parameter log-normal distribution represented by a straight line on a log-normal plot. In order to obtain exact values of the incubation times, this curve was fitted to a three-parameter distribution function F(t)

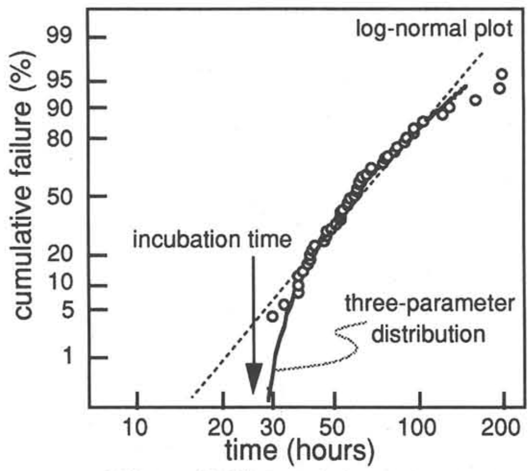
$$F(t) = \int_{\alpha}^{t} \frac{1}{\sqrt{2\pi}\sigma(x-\alpha)} e^{-(\ln(x-\alpha)-\mu)^2/2\sigma^2} dx \ , \qquad (6)$$

by a least square calculation, where α is the incubation time, σ is the dispersion and μ is the mean value of the lifetimes. The incubation time of this distribution was 26.1 hours. If the ordinary extrapolation method was applied to the curve in Fig.3, the lifetime of this interconnection, defined by the cumulative failure value 0.5%, was estimated as more than 30% shorter than the incubation time. Consequently, in the electromigration lifetime test with short lines, the reliability would be underestimated by approximating the cumulative failure curve as a straight line.

Shortening the test line length means decreasing the total number of damaged points in one test line. Almost the same results would, therefore, be obtained, if the tests were performed on interconnections having lower damage densities. Single crystal interconnections would be the case. If the total number of the damaged points in a test interconnection was smaller than 1, as an extreme case, some test lines would have no damaged points and would have longer lifetimes than the test time. In such inter-connections, the reliabilities cannot be measured by the average lifetimes or the gradients of the cumulative failure curves, which are mainly affected by major samples having longer lifetimes. The incubation time, which reflects the behavior of minor samples with shorter lifetimes, therefore, is necessary to evaluate exactly the reliability of interconnections having low damage densities.

V. Conclusions

The cumulative failure distribution plot of 200μm long Al/W bilayered interconnections curved remarkably due to the effect of shortening the test line length, and parameter log-normal distribution function represented by a straight line on a log-normal plot. The curve was fitted to a three-parameter distribution function with an incubation time. Because there were no failures caused by current stress during the incubation time, it could be used as a measure of the reliability for electromigration induced failures. Almost the same results would be obtained without shortening the test line length, if the tests were performed on inter-connections having lower damage densities, because shortening the test line length means decreasing the total number of damaged points in one test line. The incubation time, which reflects the behavior of minor samples with shorter lifetimes, is necessary to evaluate the exact reliability of such interconnections.



Al(400nm)/W(150nm) line width : 2.5 μm
current density : 6×10^{6}A/cm^2
test temperature: 120 ℃
failure definition: 10% resistance increase

Figure 3 Cumulative failure distributions of 200 μm segments. The distribution data were fitted to a three-parameter log-normal distribution curve by a least square calculation.

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