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COMPARATIVE STUDY OF STATISTICAL DISTRIBUTIONS IN ELECTROMIGRATION-INDUCED FAILURES OF Al/Cu THIN-FILM INTERCONNECTS

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In electromigration failure studies, it is in general assumed that electromigration-induced failures may be adequately modelled by a log-normal distribution. Further to this, it has been argued that a log-normal distribution of failure times is indicative of electromigration mechanisms. We have combined post processing of existing life-data from Al/Cu + TiW bilayer interconnects with our own results from Al/Cu interconnects to show that the Log Extreme Value distribution is an equally good statistical model for electromigration failures, even in cases where grain size exceeds the linewidth. The significance of such a modelling is particularly apparent in electromigration failure rate prediction.

1. INTRODUCTION

The effects of electromigration in metal conductors have been originally observed by H.B. Huntington in 1961[1]. Nevertheless, most of the quantitative understanding of this complex failure mechanism is still based on empirical formulae and arbitrary assumptions. One such assumption, widely adopted in the related literature, is that electromigration mean time to failure (MTF) obey a log-normal distribution. It was also suggested that such a distribution is in fact indicative of electromigration-induced failures[2].

This modelling of electromigration failure times, although a relatively accurate and widely used statistical tool, cannot be accepted without some scepticism. One of the known advantages of the log-normal distribution, which makes it suitable for representing failure data, is that over a reasonable range of parameters, data following other distributions will appear linear on a log-normal cumulative failure plot[4]. As a result, alternative distributions have been suggested, namely the Weibull distribution and the logarithmic extreme value distribution (LEV)[12].

Although the selection of the appropriate statistical distribution is critical for the accurate prediction of conductor reliability, the small samples commonly tested do not allow a clear distinction to be made. Isolated attempts to test large numbers of samples have concentrated on the bimodal characteristics of the distribution[11]. One of the methods allowing some sort of decision is the use of statistical models to simulate large numbers of electromigration failures. The models presented in the past deal with the determination of the most appropriate distribution[5,6,7,8]. It

has been noted that aluminum life test data fit the log-normal and the Weibull distribution equally well at relatively large failure percentages, but at the most interesting lower failure percentages show substantial discrepancies[5].

On the other hand, simulated data give a clear indication that the LEV distribution gives a tighter fit compared to both log-normal and Weibull, under a wide range of parameters. In particular it was argued that LEV distribution gives equally good results when used with grain sizes exceeding the conductor's linewidth and with grain sizes smaller than the linewidth, whereas the log-normal distribution models accurately only the latter case[6]. These conclusions were later contradicted, using smallest extreme value statistics[3,10]. Nevertheless, it should be noted that the logarithmic smallest extreme values distribution, or Type II, corresponds to a simplified Weibull distribution, quite remote from the log largest extreme values originally used[13].

The assumption that LEV distribution is a better alternative to the ones already widely used may also be theoretically justified. Given that the grain size is log-normally distributed, the time to failure of each section of the conductor should also be log-normally distributed. Since the time to failure of the entire conductor is the time to failure of a number of parallel weakest sections, statistics predict that the time to failure of the conductor should follow a LEV distribution[4,9]. The fact that Weibull grain size distributions are adequately fitted by a log-normal distribution[5] is explained by the simple fact that in any case, Weibull data fit a log normal distribution reasonably well[6].

The work presented here attempts to most suitably fit data obtained from real-life tests performed on TiW + Al/Cu bi-layer interconnects under four different test conditions in addition to one AlCu data set tested with our in-house facilities. Data were in turn fitted to a log-normal, a Weibull and a LEV distribution. Tightness of fit was examined by probability plots using the Kolmogorov-Smirnov test and the correlation coefficient.

2. EXPERIMENTAL RESULTS AND POSTPROCESSING

Post-process examined life data, supplied by Plessey, came from 4 different test runs. The test devices were 16-pin DILMONs with Al/Cu film interconnects on a TiW underlayer. The 0.15 μm TiW underlayer was preceded by a 0.03 μm Ti adhesion layer. The metals were deposited using a Varian 3180 sputterer using GEC-Plessey standard processes HE $\kappa\alpha\iota$ VJ, that is, Al/Cu backplate temperature was at 200°C and TiW temperature at 50°C.

The two layers were separated by vacuum brake and the films were unpassivated. Linewidth was 3.5 μm, exceeding the grain size. Test temperatures ranged from 183–235°C and stress current densities from 4×10^6–2×10^6A/cm^2. Life data were in turn fitted to the three distributions examined here.

It is apparent that the Weibull distribution is an inadequate model in all cases, whereas the comparison between the other two distributions is more difficult. Therefore, we have employed the Kolmogorov-Smirnov test to quantify the goodness of fit. The critical values obtained are quite high and we have used them as figures of merit for each distribution. The results are shown in Table I. A least squares test has confirmed these results as well.

TABLE I
Max |xi − Ei| values (Ei = expected rank, xi = rank).

Data set	Log normal	LEV	Weibul
Al/Cu + TiW, #1	0.089	0.047	0.141
Al/Cu + TiW, #2	0.133	0.073	0.182
Al/Cu + TiW, #3	0.087	0.055	0.143
Al/Cu + TiW, #4	0.124	0.086	0.165
Al/Cu, #5	0.194	0.183	0.210

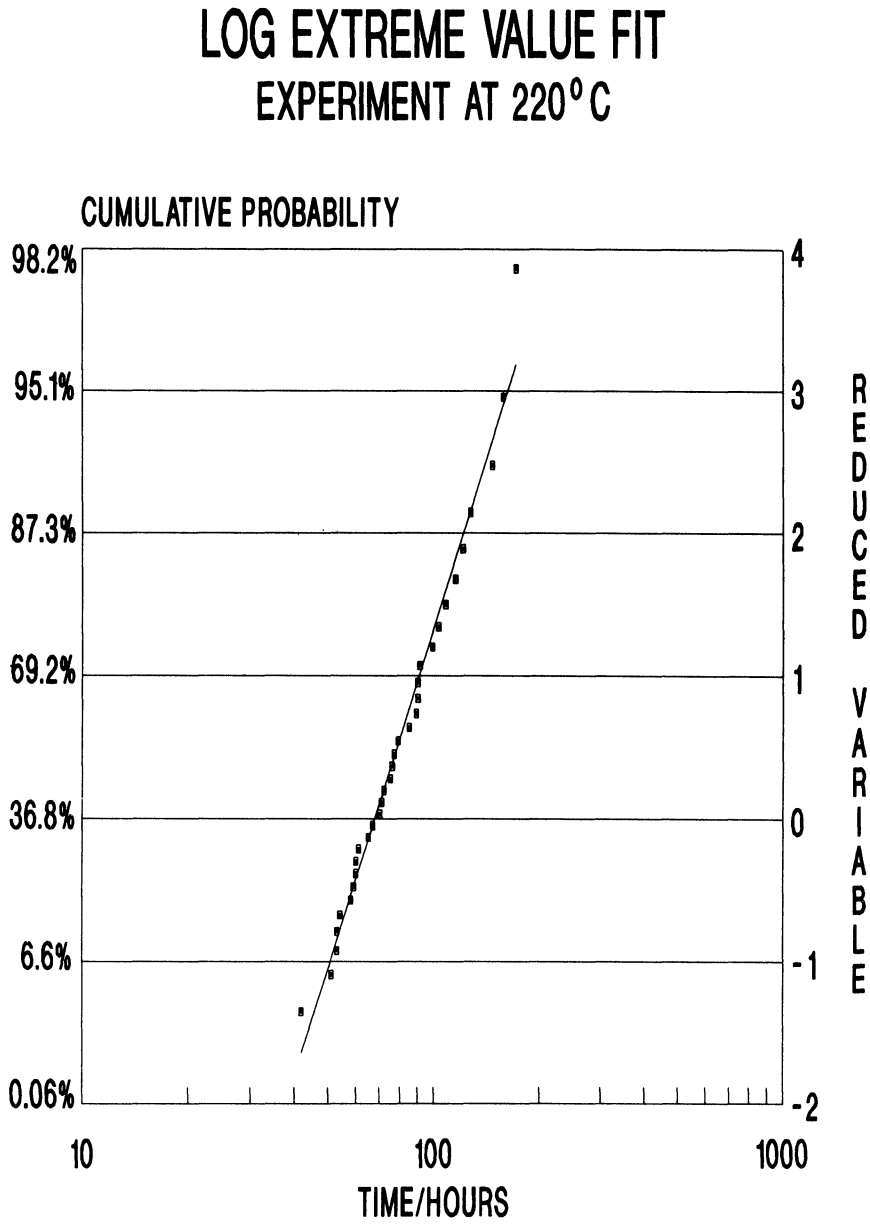

FIGURE 1 LEV Modelling: AlCu Film.

A graphical representation of the results for the three distributions is shown in Figures 1, 2 and 3 respectively. We have selected test run #3 as a representative because this was the largest sample tested. Nevertheless, data followed a more or less expected behavior regarding both their distribution and their MTF in all other test runs.

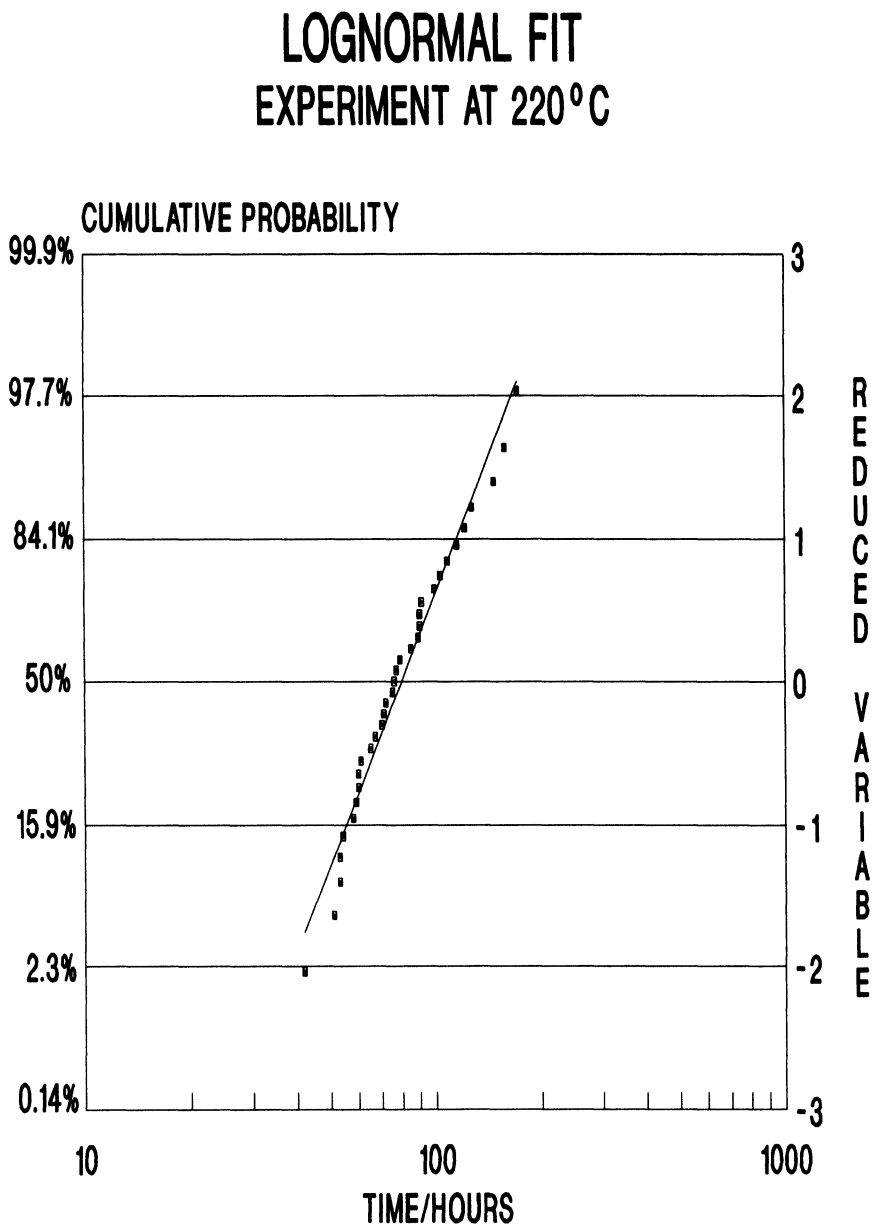

FIGURE 2 Log-normal Modelling: AlCu Film.

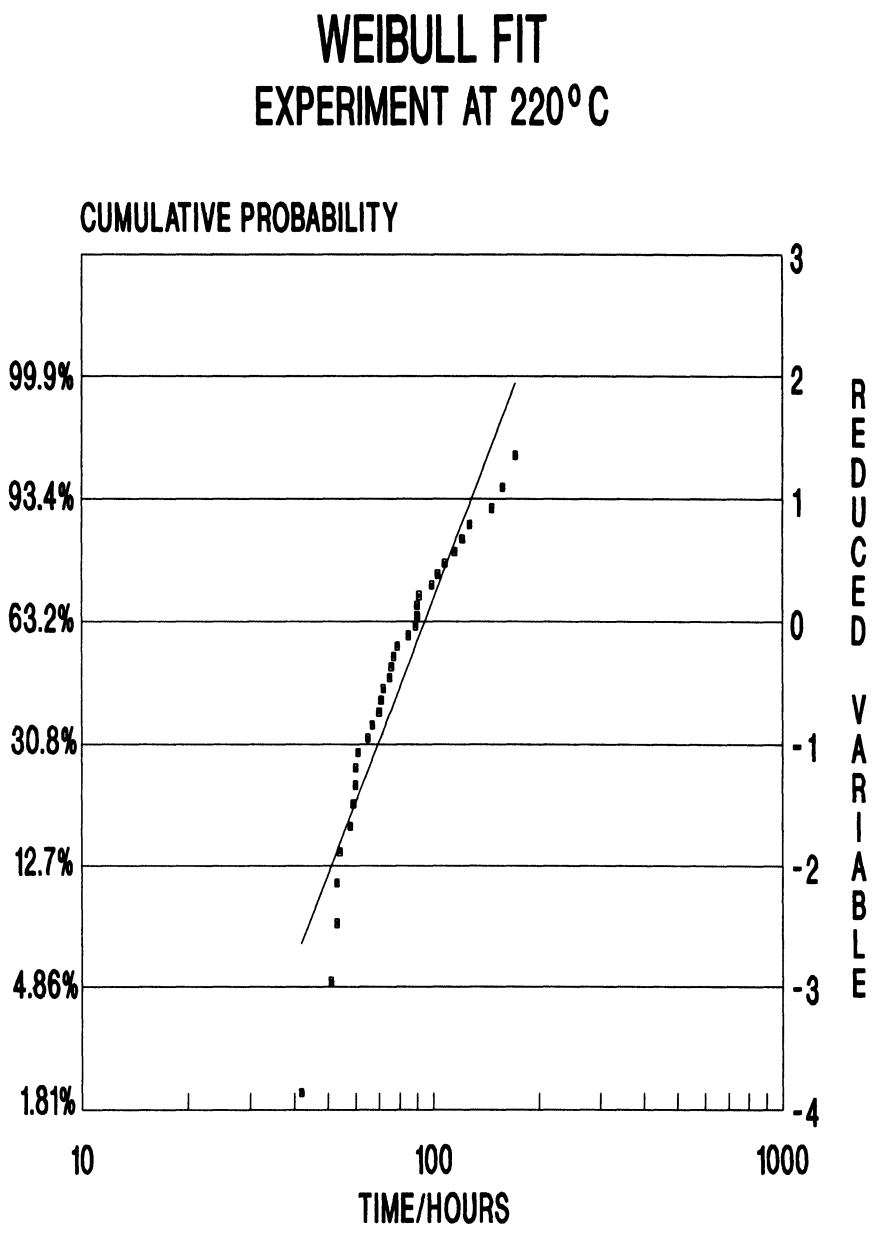

FIGURE 3 Weibull Modelling: AlCu Film.

Further to the post processing of existing life data, we have performed our own in-house tests. A test facility has been designed and implemented, comprised of an oven, DC current sources, and an HP measurement and control system. The samples tested were AlCu film interconnects, supplied again by Plessey. The 3.0 μm linewidth exceeded the film grain size in this case as well.

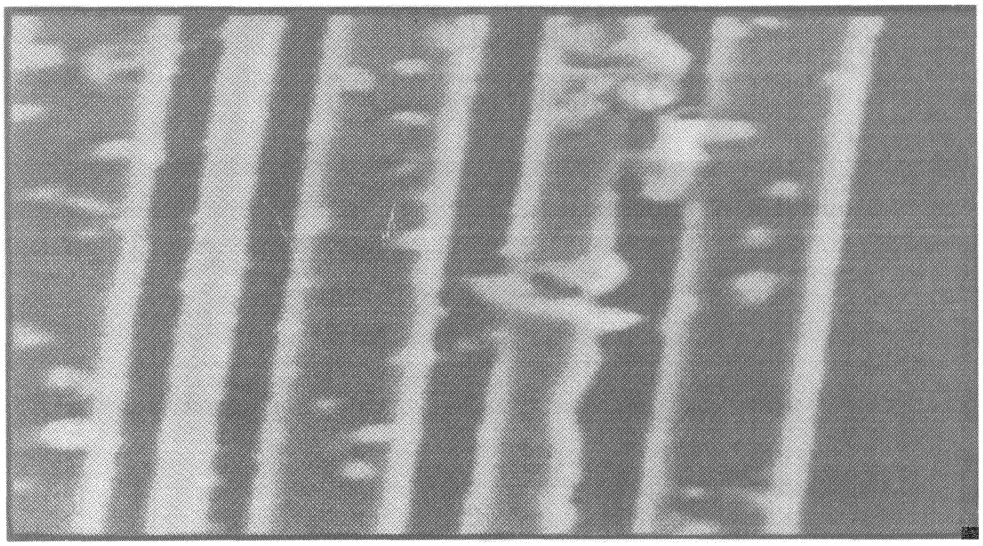

FIGURE 4 Characteristic electromigration failure due to an open circuit formation. Areas of extrusions are also visible.

Failure was assumed when dR became greater than 20% of the initial resistance values, according to common practice. Although failure time was recorded, stressing of the failed samples was not halted, resulting in an open circuit for all tracks until the time of the last failure. The first 2 samples failed after 2 hours, quickly followed by another 3 samples. The last sample failed after 155 hours of stressing (Figure 4). The early failures were expected due to the high test temperature and

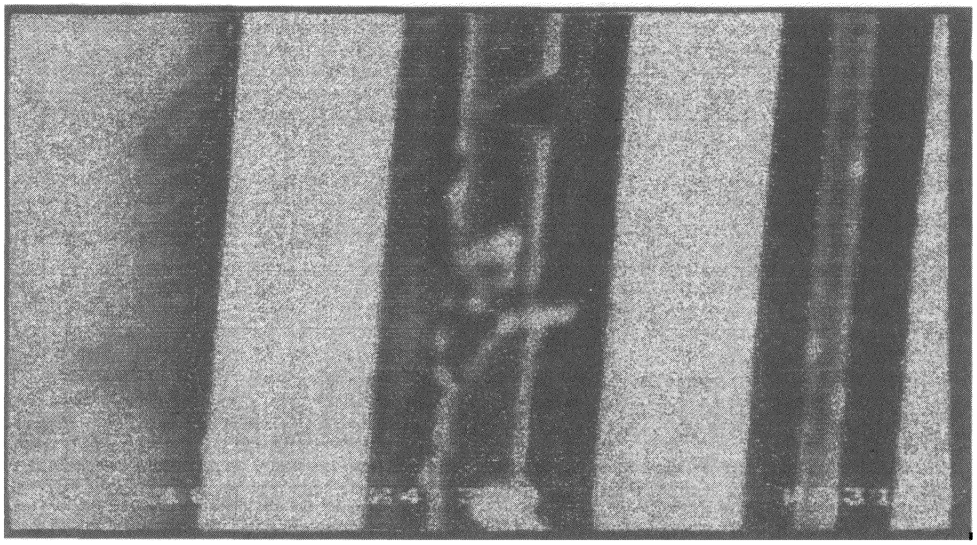

FIGURE 5 Another characteristic open-circuit failure due to electromigration. The triangular void is due to the thermal stress that preceded the electromigration tests.

TABLE II
MTF values for the three distributions examined.

Distribution	LN	LEV	Weibull
MTF	13 hours	10 hours	20 hours

stress current (230°C, $4 \times 10^6 A/cm^2$). The samples had also been heated for a number of hours before the test started for calibration and software debugging purposes. This might have also reduced the MTF slightly (Figure 5).

We have fitted these life data again in turn to a log-normal, LEV (Gumbel distribution of the logarithms of life data) and a Weibull distribution. The MTF values for each distribution are shown in Table II.

There is an expected increase of the MTF (t50) going from the LEV to the Weibull distribution, since the LEV modelling is more pessimistic and the Weibull modelling more optimistic, when both are compared to the log-normal one.

The Kolmogorov-Smirnov was again employed to quantify goodness of fit. The result, shown in Table I as test run #5, indicates that LEV distribution is an adequate model for the specific Al/Cu interconnects tested.

3. CONCLUSION

It has been shown that life data from five different electromigration tests on TiW + Al/Cu bi-layer and AlCu mono-layer thin film interconnects are tighter fitted to a log extreme value distribution compared to a Weibull or a log-normal one. In all cases, linewidth exceeded the median grain size of the films. This has a particular significance when it comes to predicting the reliability of thin-film interconnects as shown by the results presented here.

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