

JEDEC STANDARD

Standard Method for Calculating the Electromigration Model Parameters for Current Density and Temperature

JESD63

FEBRUARY 1998

ELECTRONIC INDUSTRIES ALLIANCE

JEDEC Solid State Technology Association



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Published by
JEDEC Solid State Technology Association 2000
2500 Wilson Boulevard
Arlington, VA 22201-3834

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STANDARD METHOD FOR CALCULATING THE ELECTROMIGRATION MODEL PARAMETERS FOR CURRENT DENSITY AND TEMPERATURE

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STANDARD METHOD FOR CALCULATING THE ELECTROMIGRATION MODEL PARAMETERS FOR CURRENT DENSITY AND TEMPERATURE

(From JEDEC Council Ballot JCB-97-17, formulated under the cognizance of JC-14.2 Committee on Wafer-Level Reliability)

1 Scope

1.1 The method provides procedures that use linear regression analyses for calculating sample estimates, and their confidence intervals, of the electromigration model parameters for current density and temperature of thin-film metal interconnects used in microelectronic devices.

1.2 The method assumes that the median time to failure (t_{50}) data from accelerated stress tests of metal interconnect test structures can be satisfactorily modeled by Black's equation [1] (see eq. 3.2). Hence, the model parameter for current density, J , is the value of the exponent, n , to which J is raised and the model parameter for temperature is the activation energy, E_A , of the electromigration process. The linear regression analyses calculate sample estimates of E_A directly, while sample estimates of n are obtained from analyses that involve the calculation of sample estimates of a slope S , where $S = -n$.

1.3 The method requires existing failure-time (t_f) data or median-time-to-failure (t_{50}) data. When t_{50} data is used, they must be from **at least three** electromigration stress tests conducted at different stress levels when only the current density or only the temperature is varied. They must come from **at least four** stress tests if both current density and temperature are varied to obtain the t_{50} data.

1.4 The method can be used with censored t_f data if JEDEC standard JESD37 [2] (or its equivalent) is used to convert the censored data to t_{50} estimates and the method used with these t_{50} values. In the context of this standard, censored t_f data refers to the case where the stress test is halted before all test parts have failed. Hence, the number of t_f values available for analysis is less than the sample size of the test.

1.5 Examples of three types of calculations by this method are given in Annex A. One is to obtain sample estimates of n and of their confidence interval when t_{50} or t_f data are available from experiments conducted at different current-density stresses. The second is to obtain sample estimates of both n and E_A and of their confidence intervals when t_{50} or t_f data are available from experiments conducted at different current-density and temperature stresses. The third involves calculations with censored data.

1.6 This method does not preclude the use of other methods as long as they have been shown to provide equivalent results. The calculation examples referred to in 1.5 may be used to show equivalence.

2 Introduction Significance and use

2.1 Electromigration is a failure mechanism of electrical interconnects that is of great concern, especially for the reliability assessment of very large scale integrated (VLSI) microelectronics. The drivers of the electromigration process in Black's equation are the current density and the temperature.

2 Introduction Significance and use (cont'd)

2.2 To obtain reliability data from thin-film metal interconnect test structures in a time much shorter than their expected lifetime, samples of similar interconnects are subjected to accelerated stress tests. These tests provide sets of failure times for current density and temperature conditions that are more severe than would normally be encountered in use. To assess the reliability of such parts **under use conditions** requires that the model parameters for both current density (n) and temperature (E_A) be determined and used to extrapolate the results of stress tests to use conditions. Because only sample estimates of the model parameters can be obtained, it is also important to determine the confidence limits for these sample estimates.

2.3 Confidence intervals for the sample estimates of the model parameters of electromigration are necessary to determine the statistical significance of any differences noted in the values determined: from similar interconnect test structures measured at different times, from test structures with different designs, or from interconnects fabricated at different times, at different laboratories, or with different processes.

2.4 This method can be useful in evaluating and optimizing the selection of metal alloys and processes, and in identifying the key input material and process parameters that affect the reliability of interconnects.

3 Summary of method

3.1 To obtain sample estimates and their confidence intervals of the model parameter for the current density, for the temperature, or for both requires a set of median-time-to-failure (t_{50}) data or a set of time-to-fail (t_f) data obtained from several electromigration stress tests with different stress conditions. These data are best obtained by following the procedure of the standard electromigration test method [3] and the standard method for determining the joule heating in a test line [4]. The electromigration test method includes procedures for calculating sample estimates of both t_{50} and σ from the failure times of the test parts. The sample estimates for t_{50} and σ are obtained from the average and the standard deviation, respectively, of the natural logarithm of the individual failure times. That is,

$$\hat{t}_{50} = \exp [\ln t_f(j)]_{av}; \hat{\sigma} = [\ln t_f(j)]_{sdt. dev.}, \quad (3.1)$$

where j runs from 1 to N and N is the sample size. The test method also includes procedures for calculating the confidence intervals for these estimates. In that method [3], as in this method, the impact of sample size on confidence intervals is demonstrated. In performing such electromigration tests and in following this method, it must be understood that the stress temperature of the structures being stressed is the **sum** of the local ambient stress temperature and of the temperature increase of the test line due to power dissipation in the test structure and elsewhere on the wafer or chip (see 4.4).

3 Summary of method (cont'd)

3.2 Assumptions

3.2.1 The method assumes that the set of t_{50} or t_f values can be modeled by Black's equation:

$$t_{50} = \frac{A}{J^n} \times \exp\left(\frac{E_A}{kT}\right), \quad (3.2)$$

where:

J is the current density in the metal test lines (A/cm^2),
 n is the model parameter for current density,
 E_A is the model parameter for temperature, i.e. activation energy (eV),
 T is the temperature of the metal test lines (K),
 k is Boltzmann's constant (8.617×10^{-5} eV/K), and
 A is a constant.

3.2.2 When dealing with failure-time data, t_f to determine n or E_A , it is assumed in 5.2, 6.2, and 7.2 that there is no censoring of these data. If there is data censoring in some or all of the tests, the t_f data from all tests must be used to obtain sample estimates of t_{50} in the manner described in section 8. These sample estimates of t_{50} are then used to obtain sample estimates of n, E_A , or both as described in 5.1, 6.1, and 7.1, respectively.

NOTE — Using t_{50} data rather than the failure-time (t_f) data to obtain sample estimates of n, E_A , or both, results in an increase in the length of the confidence interval for these estimates. The reason for the increase is that the level of information from the individual t_f values is reduced in the process of subsuming them in the t_{50} data. But, the larger the number of experiments involved in calculating the sample estimates, the less significant will be this increase. The expected value for the ratio of the confidence interval (I_{50}) from t_{50} data to the interval (I_f) from t_f data can be estimated from:

$$\frac{I_{50}}{I_f} \approx \frac{t\left(1 - \frac{\alpha}{2}; N - p\right)}{t\left(1 - \frac{\alpha}{2}; N_s - p\right)}$$

where:

N is the number of stress tests (t_{50} values),
 N_s is the sum of the numbers of test structures in the N stress tests,
 $1-\alpha$ is the confidence coefficient for the confidence interval, and
 p = 2 when **either** J or T is varied among the tests to obtain sample estimates of n or E_A , and
 p = 3 when **both** J and T are varied to obtain sample estimates for both n and E_A .

See examples described in Annex A, paragraphs A.2.2 and A.4.3.

3 Summary of method (cont'd)

3.3 Sample estimates for n or E_A are obtained from a linear regression analysis for one independent variable (sections 5 and 6). The analysis requires failure-time data from several electromigration stress tests when these tests are conducted at different levels of current-density or temperature stress, respectively. When both current density and temperature are varied, sample estimates are obtained from a multiple linear regression for two independent variables (section 7).

3.3.1 If the current density is varied while the stress temperature of the metal test lines is kept constant in a number of electromigration stress tests, then t_{50} will be proportional to $1/J^n$ and hence

$$\ln t_{50} = -n \ln J + B, \quad (3.3a)$$

or

$$\ln t_{50} = S \ln J + B, \quad (3.3b)$$

where B is a constant involving A and E_A . A plot of $\ln t_{50}$ versus $\ln J$ will display data points aligned generally along a straight line. This is illustrated in figure 1A. A linear regression analysis of the $\ln t_{50} - \ln J$ data pairs will yield a least-squares, sample estimate of the slope, S , of the best-straight-line fit to the data and the confidence interval for this slope. The sample estimate for n , the model parameter for the current density, is obtained from the relation $S = -n$. The method depends critically on the assumption of linearity (see 4.1, 4.2, and 9.). A very useful tool in assessing the validity of the assumption is a visual inspection of the plotted data (see 9.2).

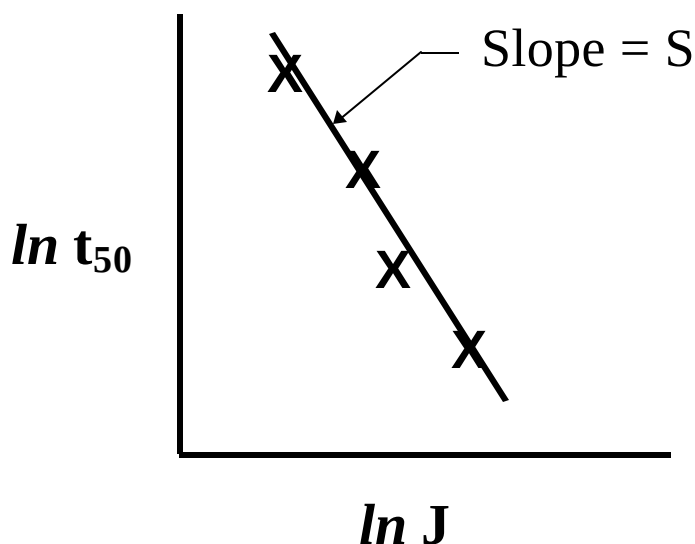


Figure 1A — Plot of $\ln t_{50}$ versus $\ln J$ to illustrate the behavior of eq. 3.3b and the best-straight-line fit to the data from which the value of n can be obtained and the linearity of the dependence may be judged.

3 Summary of method (cont'd)

3.3.2 If the temperature of the test lines is changed while the current-density stress is kept constant in a number of different stress tests, then t_{50} will be proportional to $\exp(E_A/kT)$ and hence

$$\ln t_{50} = \frac{E_A}{k} \times \frac{1}{T} + C, \quad (3.4)$$

where C is a constant involving A and n . A plot of $\ln t_{50}$ versus $1/T$ will display data points aligned generally along a straight line. This is illustrated in figure 1B. A linear regression analysis of the $\ln t_{50} - 1/T$ data pairs will yield a least-squares, sample estimate of the slope of the best-straight-line fit to the data and of the confidence interval for this slope. The slope of this line is E_A/k , the activation energy divided by Boltzmann's constant (8.617×10^{-5} eV/K). The method depends critically on the assumption of linearity (see 4.3 and 9). A very useful tool in assessing the validity of the assumption is a visual inspection of the plotted data (see 9.2).

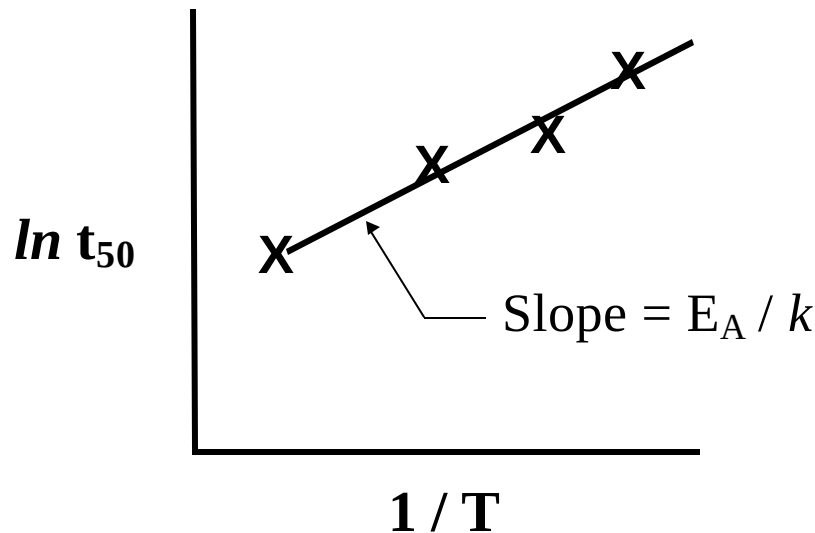


Figure 1B — Plot of $\ln t_{50}$ versus $1/T$ to illustrate the behavior of eq. 3.4 and the best-straight-line fit to the data from which the value of E_A can be obtained and the linearity of the dependence may be judged.

3.4 The method offers procedures for calculating sample estimates and their confidence intervals for either S , E_A , or both, depending on the data available. Values for the sample estimates for n and their confidence intervals are obtained by recognizing that $S = -n$.

3 Summary of method (cont'd)

3.4.1 When only t_{50} values are available and they are given either as a function of current density or of temperature, then the procedure leads, accordingly, to a sample estimate and confidence interval for either S or E_A . See 5.1 and 6.1, respectively. If the sample sizes for the different experiments are available, their effect is included in the procedure.

NOTE — This procedure is useful when evaluating reported values for n or E_A (with t_{50} data), and any conclusions derived therefrom, when information about the confidence intervals for these values are not provided.

3.4.2 When failure times, t_f , are available from experiments to determine the dependence of t_{50} values on either current density or temperature, then the procedure leads, accordingly, to a sample estimate and confidence interval for either S or E_A . See 5.2 and 6.2, respectively.

3.4.3 When t_{50} or t_f data are available from experiments where both temperature and current density were varied, then the procedure provides a means for calculating sample estimates and confidence intervals for both S and E_A . See 7.1 and 7.2.

3.4.4 When censored t_f data (instead of complete data) are available from all or some experiments, where either the current-density, the temperature, or both stresses are different, then the procedure provides a means for calculating sample estimates and confidence intervals for S , E_A , or both. See section 8.

4 Precautions and interferences

4.1 In calculating the model parameters with t_{50} data, it is assumed that the t_{50} data comes from a population where the sigma is constant over the range of test conditions used to determine $\hat{S}$ and $\hat{E}_A$. The method is still robust when there are variations in sigma over the range of conditions that might be used. But, a statistically different sigma at one or more these stress conditions of the experiment may be an indication of a change in the operation of the electromigration process at these conditions that could affect S , E_A , or both.

4.2 If errors are made in estimating the joule heating of test lines, the linearity assumption of 3.3.1 may not be valid. If the joule heating is systematically underestimated, or ignored entirely, a plot of $\ln t_{50}$ versus $\ln J$ will follow a curve whose slope becomes increasingly more negative with increasing current density.

4.3 The activation energy for electromigration through the metal lattice is higher than that along the grain boundaries of the metal film. For metal interconnect lines with metal grains whose median size is comparable with or larger than the line width, significant migration may occur through the lattice within the temperature range used in the stress tests to determine E_A . In this case, the assumption of linearity in 3.3.2 will not be valid. A plot of $\ln t_{50}$ versus $1/T$ will indicate any significant indication of nonlinearity. For such metal interconnects, it will be necessary to evaluate if tests can be conducted at different ranges of temperature to separate competing mechanisms.

4 Precautions and interferences (cont'd)

4.4 The method provides procedures to calculate the sample estimates of S and E_A and their confidence intervals where it is assumed that all test parts in a given accelerated stress test were subjected to the same current-density and temperature stresses. But, this is only an idealization of actual conditions. For example, even if the current through each test line is the same and is held constant throughout the test, some small variations in the width and thickness of the test lines will invariably exist and result in variations in the current-density stresses among the test structures stressed in a given test. The stress temperature of a test line is the sum of 1) the ambient temperature provided by an oven or a hot chuck (for wafer-level tests), 2) the temperature increase due to power dissipation in the test structure caused by the stress current, and 3) the temperature increase in the test line due to power dissipation elsewhere on the wafer or chip. Therefore, differences and changes with time are also expected for the stress temperatures of the lines under test. There will be some variation in the resistance of the structures under test and each will exhibit a different change in resistance with test time. Variations and changes in the magnitude of the other components to the stress temperature may also be expected. When these variations are relatively small, see 4.5. When they are larger, see 4.6.

4.5 Small random variations in the current-density and temperature stresses to which the test lines are subjected in a given stress test can be tolerated without significantly degrading the quality of the estimates of the confidence intervals. This can be done by using the means of the measured test line temperatures and of the estimated current densities in the procedures of the method.

NOTE — It has been assumed that the population of $Y_{ij} = \ln t(J_i, T_i, j)$ values for the i -th test, are normally distributed with a mean of $\ln t_{50}$ and a variance of σ^2 , where $t(J_i, T_i, j)$ is the failure time of the j -th line to fail in the i -th test and where the stress conditions are J_i and T_i . The effect of variations in the stress conditions can be modelled [5] by adding to Y_{ij} an independent random variable, v_j , that is normally distributed with a mean of zero and a variance of v^2 . The new population will still have a mean of $\ln t_{50}$, but it will have an increased variance of $\sigma^2 + v^2$. The relative effect of the variations on the new sigma of the population, $\sigma_{\text{new}} = (\sigma^2 + v^2)^{1/2}$, only becomes significant when v becomes comparable to σ . When the v_j values are small, the variations in Y_{ij} propagate as fractional variations of the original time to fail, $t(J_i, T_i, j)$. Percent variations of as much as 20% in the $t(J_i, T_i, j)$ values ($v = 0.20$) will lead to an increase in σ_{new} of not more than 20.2%, if $\sigma = 0.30$ or larger. Variations in J and T of 5% and 5°C, respectively, can each produce variations of approximately 15% in $t(J_i, T_i, j)$. The variations in $t(J_i, T_i, j)$ as a result of the two processes in combination, will increase a sigma of 0.3 to not quite 0.37.

4.6 When analyzing the results of accelerated stress tests where there had been known and relatively large variations in the current-density and temperature stresses of the test lines, use procedure 7.2.1B.