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Method for Characterizing the Electromigration Failure Time Distribution of Interconnects Under Constant-Current and Temperature Stress

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METHOD FOR CHARACTERIZING THE ELECTROMIGRATION FAILURE TIME DISTRIBUTION OF INTERCONNECTS UNDER CONSTANT CURRENT-DENSITY AND TEMPERATURE STRESS

(From JEDEC Board Ballot JCB-05-59, formulated under the cognizance of the JC-14 Committee on Quality and Reliability of Solid State Products.)

1 Scope

This is an accelerated stress test method for determining sample estimates and their confidence limits of the median-time-to-failure, sigma, and early percentile of a log-Normal distribution, which are used to characterize the electromigration failure-time distribution of equivalent metal lines subjected to a constant current-density and temperature stress. Failure is defined as some pre-selected fractional increase in the resistance of the line under test. Analysis procedures are provided to analyze complete and singly, right-censored failure-time data. Sample calculations for complete and right-censored data are provided in Annex A. **The analyses are not intended for the case when the failure distribution cannot be characterized by a single log-Normal distribution.**

2 Significance and use

2.1 Electromigration failure mechanism

Electromigration is a metallization failure mechanism that leads to excessive increases in resistance or even an open circuit in metallizations. It is important to those who are concerned about the reliability of electrical interconnections in microelectronic circuits and devices. The stress drivers for this failure mechanism are current density and temperature. The method is used to provide failure-time data for: assessing metallization reliability, making major decisions for the selection of metallization and processing technologies, and monitoring process control. Failure is defined as some fractional increase in the resistance of a test line.

2.2 Model for electromigration

The method assumes that Black's equation [1] (eq. 1) can satisfactorily model how the sample estimate of the median-time-to-failure, t_{50s}, (from an accelerated electromigration stress test) depends on current density and temperature. The model parameters for temperature and current density are, respectively: the activation energy, E_a, and the value of the exponent, n, to which the current density, J, is raised.

$$t_{50s} = A\,\frac{\exp\left(E_a / kT\right)}{J^n} \tag{1}$$

where:

A is a constant;
n is a constant;
J is the mean current density of the test lines stressed;
E_a is the activation energy;
k is Boltzmann's constant ($8.62 \cdot 10^{-5}$ eV/K); and
T is the mean stress temperature of the test lines stressed.

NOTE Experimental determinations of model parameters n and Ea may be obtained by use of JEDEC standard JESD63 [2].

2 Significance and use (cont'd)

2.3 Test vehicles (Al and Cu)

The test vehicle is a four-terminal, thin-film, metal test line structure where the failure criterion is either an open circuit or a prescribed percent increase in the resistance of the line. Test lines may include contacts and vias to different metallization levels. The metal lines are made of aluminum- or copper-based, thin-film metallizations that are intended for use in microelectronic circuits and devices. The test line will consist of a primary conductor of aluminum or copper, and usually an adjoining thinner and higher resistivity conductor film. Aluminum metallizations may include a higher-resistivity, adjoining conductor film that can bypass an opening in the primary conductor due to electromigration. Test lines may have additionally adjacent-running lines that can serve as extrusion monitors. Copper metallizations will generally be of a damascene construction and be enclosed by a thin, higher-resistivity, adjoining copper-diffusion-barrier film. In both cases, these higher resistivity films are designed to conduct only a small fraction of the current in the undamaged test line.

2.4 Wafer- and package-level test

The method allows the test line to be stressed on a heated stage while still part of the wafer (or portion thereof) or stressed in an oven while bonded in a package and electrically accessible via package connections.

2.5 Applications

The method is intended for use as a referee method by different testing facilities and for use at testing stations for comparing different metallizations and different processing procedures, and for monitoring product reliability. It can be used as a tool in qualifying vendors and in determining the use-life of a metallization. It can also be used as an instructional instrument to aid first users and to alert the user to potential measurement interferences that could impact the accuracy of the sample estimates.

2.6 Lower limit on t_{50}

The method is normally intended for use under stress levels where the median-time-to-failure, t_{50}, is of the order of hours. Greater stress levels can be used to reduce the test time as long as the time to achieve the stress temperature in the test lines is less than a small fraction of t_{50} and no new failure modes or significant material changes are stimulated by the higher stress.

3 Terms and definitions

3.1 metallization: A thin-film metallic conductor used to interconnect microcircuit elements.

NOTE In addition to the primary, low-resistivity metal conductor, the metallization may include a thin, higher-resistivity adjoining film.

3.2 test line: A metallization line of specified dimensions, with or without vias making connections to over- or under-lying metal levels, whose length is defined by the location of two voltage taps used to make Kelvin-like resistance measurements of the test line when two other terminals force a current through the line.

NOTE It is assumed that the major portion of the test-line length will have a uniform cross-sectional area.

3.3 test structure: A passive metallization structure, including a test line, that is fabricated on a semiconductor wafer by procedures used to manufacture microelectronic integrated devices.

3.4 test chip: A part of a wafer, containing one or more test structures, that is stressed according to the test method either at the wafer level or in a package.

4 Summary of method

4.1 Procedure

The method involves subjecting a sample of N test lines to high current-density and high ambient temperature stress, calculating the mean stress temperature of the test line (which includes any Joule heating) before any significant electromigration damage can occur, and measuring the time to failure of each test line, t.

A test is performed to determine if the experimentally determined failure times can be modeled by a single log-Normal distribution with the parameters t_{50} (median time to failure) and σ (sigma).

If the test is conducted until all parts on test have failed, so that the fail time data is complete, then the sample estimate of the median-time-to-failure, t_{50s}, for the stress conditions used in the test, is given by the exponential of the mean of the logarithms of the time-to-failure values:

$$t_{50s} = \exp[(\ln t)_{mean}] \tag{2}$$

And, the sample estimate of the sigma of the distribution, s, is given by the standard deviation of the logarithm of the time-to-fail values:

$$s = \sqrt{\sum_{i=1}^{N} (\ln t_i - (\ln t)_{mean})^2 \Big/ (N-1)} \tag{3}$$

4 Summary of method (cont'd)

4.1 Procedure (cont'd)

Confidence limits for the sample estimates of t_{50} and s are calculated with the use of the t-distribution and the chi-squared distribution, respectively. The p-th percentile of the fail time distribution, t_{ps}, is computed from $t_{ps} = \exp(t_{50s} + z_p s)$, where z_p is the p-th percentile of the standard normal distribution. Estimated confidence limits for t_p are calculated using the noncentral t-distribution.

If the test is halted before all parts on test have failed, so that the fail time data is censored, then a method based on the Persson and Rootzen approach is used, which gives closed-form estimators of t_{50} and sigma. Approximate confidence limits for t_{50}, sigma, and t_p are developed from the work of Meeker using the Normal-approximation method.

4.2 Test options

Three testing options are included in the test method, each involving somewhat different considerations:

Option 1 - The test structures to be stressed are part of either the entire or some portion of a wafer that is placed on a heated stage. The test structures are contacted by individual or a fixed array of probes and are stressed sequentially. This requires the dedication of a wafer-probe station.

Option 2 - Each test structure is individually packaged and stressed in a temperature-controlled oven. The thermal response time of a packaged test structure is dependent on the size and design of the package and may be of the order of several minutes. Therefore, if Joule heating is significantly large, the measurement of the stress temperature of the test line at the beginning of the test will need to be delayed until the test line is in thermal equilibrium with its package.

Option 3 – Adjacent lying test lines on a wafer or in a package are stressed at the same time. Part of the heat path to the stress ambient of each test line is shared by the others. Hence, the test lines communicate thermally with each other during the stress test. For this reason, the option may, in addition, require a calculation of a thermal resistance that is used to calculate the mean stress temperatures of the test lines as each fails and the total power dissipation decreases.

4.3 Parameters to be selected

Before the test method can be implemented, a number of parameters must be selected and agreed upon by the parties to the test.

4.3.1 Select the *ambient stress temperature*, which is the temperature of the heated stage for wafer-level testing and that of the oven for package-level testing. See 5.12 for test lines with low-k dielectrics.

4.3.2 Select the *current-density stress* in the primary conductor of the test line (see 6.4).

4.3.3 Select the *temperature, T_n*, to which the failure-time data shall be normalized (5.10).

4.3.4 Select the *failure criterion* (5.4).

4 Summary of method (cont'd)

4.3 Parameters to be selected (cont'd)

4.3.5 Select the *number*, N, *of* the *lines* to be stressed.

NOTE Both N and the sample estimate of sigma (eq. 3) are used in 9.2 to determine the confidence limits for the sample estimates of t_{50} and σ when all test lines have failed.

4.3.6 Select the *design width, thickness, and length* of the test lines to be used (see 5.11 and 5.4.3)

4.3.7 Select the value of the *activation energy*, E_a (5.10).

4.3.8 Select the *confidence percentile* to be used.

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5 Precautions and interferences

5.1 Errors in mean current density and temperature stresses

Errors in estimating the mean current density and temperature stresses will lead to errors in the sample estimate of t_{50} (i.e. t_{50s}) that can be calculated from eq. 1. For example, calculations for aluminum metallizations [3] indicate that the induced percent error in t_{50s} can be between two and three times the percent error in estimating the current density and can be between 15% and 20% if there is a 5 ˚C error in estimating the stress temperature between 150 ˚C and 200 ˚C.

5.2 Deviations from the stress means

Deviations from the stress means of current density and temperature of the individual test lines produces changes in the time to failure, t, of these test lines. These changes lead, in turn, to increases in the sample estimate of sigma, s, and in the confidence limits for t_{50} and sigma. Deviations should be kept small enough that they do not produce changes in t by more than 20% [3]. This is especially important when sigma is less than 0.4. The effect of stress deviations on t is calculated from eq. 1 by substituting t for t_{50s}.

5.3 Thermal interactions

Thermal interactions can interfere with making accurate estimates of the mean stress temperature of individual test lines during the test. Such interactions need to be considered when the following two conditions exist: 1) when the stress current density is large enough to cause significant Joule heating in the test lines and 2) when a number of adjacent lying test lines on a chip in a package or on a wafer are stressed at the same time.

Thermal interactions among the test lines can be important when a portion of the heat path from each test line to the stress-temperature ambient is shared. In packaged test lines, an obvious shared heat path is through the interface between the bottom of the chip and the package and through the package to the high-temperature ambient of the oven in which the package is housed. The temperature drop across the interface and through the package will be equal to the product of the power dissipated by the test lines and the thermal resistance associated with the heat path in the interface and package.

5 Precautions and interferences (cont'd)

5.3 Thermal interactions (cont'd)

If, for example, each test line fails because of an open circuit, then as each line fails the remaining lines on the test will be subjected to a step-wise decrease in stress temperature (see 6.7 and 8.8.2).

In contrast to packaged test lines, thermal interactions of test lines on a wafer will generally be negligible. This is because the thermal resistance associated with the interface between the bottom side of the wafer and the top surface of the heated stage is generally negligible in comparison to the thermal resistance associated with the heat paths through the silicon chip and through any intervening dielectric layers between the test line and the silicon chip. But, if there is poor thermal contact at this interface then significant thermal interactions among the test lines may occur (see, for example, Figure 6 in ref. 4). If test lines are sufficiently closely spaced, some overlapping of the heat paths in the silicon and the intervening dielectric layers may occur that will also lead to thermal interactions.

A direct way to test for the existence of significant thermal interactions among test lines is to monitor the resistance of one test line as a current sufficient to cause measurable Joule heating is switched on in another test line. An increase in resistance of the first line is indicative of a thermal interaction.

5.4 Selecting a percent change in resistance for the failure criterion

5.4.1 Aluminum metallizations

Open-circuit line failures are seen in aluminum lines with no adjoining high-resistivity films. Such lines usually exhibit a significant increase in line resistance only near the end of life. Hence, if a relatively high percent increase in resistance is selected for the failure criterion no significant difference in the time to failure is incurred by not waiting for essentially an open circuit to occur.

5.4.2 Multilayer metallizations

The use of a relatively small percent increase in resistance as a failure criterion is necessary when testing multilayered metallizations. Such metallizations usually have an adjoining refractory metal film for aluminum-based conductors or have a higher resistivity, diffusion-barrier adjoining film for copper-based conductors. The use of higher resistivity adjoining films in these metallizations usually prevents an open-circuit failure of the test line. Using too high a percent increase may affect significantly the sample estimates of the activation energy, value for n, and t_{50s} [5]. The use of percent increases greater than 30% has been reported to lead to large variability in test results [5] and to resistance oscillations due to the formation of open circuits in all but the adjoining refractory films, when testing unpassivated aluminum-based metallizations [6].

5.4.3 Effect of line length

When selecting a value for the percent increase in resistance as a failure criterion, it should be recognized that this value represents a measure of the amount of metal movement or voiding in the metal line that must occur *relative to its length* before failure is declared. Hence, to make fair comparisons between the results of tests using different lengths, the failure criterion used in these tests must be adjusted for the difference in length. A corollary is that in any given test, all the test lines must be of the same length, otherwise an overestimate of the sigma and an uncertain error in t_{50s} will be made. (See 4.3.6.)

5 Precautions and interferences (cont'd)

5.5 Excluding test lines

The scatter of measured values for the resistance of test lines in a test, $R(\mathrm{tl})_L$, will usually be characterized by a normal distribution with a small standard deviation. Abnormalities in a test line, other than those that were detectable from a visual inspection (6.5), may be revealed by a resistance that can be considered to be an outlier from the distribution [7]. This line should be excluded from the test if the intent of the test is to evaluate the test procedure, conduct an inter-laboratory experiment, or compare different metallizations or different processing procedures. If the intent of the test is to characterize a product, including all inherently possible defects and causes for variability, then such an outlier may be included if it is so noted in the report of the test.

NOTE The test criterion for a single suspected outlier, T(n;%), is the difference between its value and the mean of all values, divided by the standard deviation of all values [7]. T(n;%) is a function of the number of lines measured and the significance level selected. If outliers may be either too large or too small, but not both, use the one-sided test values for the level of significance in Table 1 of reference 7. If otherwise, use Table 1 and the column for one half the significance level selected.

5.6 Limit on applied voltage

The limit on the voltage imposed on the test line (7.3) is intended to avoid the possibility of an immediate healing of an open circuit failure due to arcing.

5.7 Recovery from failure

For passivated aluminum test structures, it is possible that a test line having failed by an open circuit will resume conduction spontaneously later in the test or after the stress conditions are interrupted for a period. Temporary interruption of conducting test lines may also result in some recovery in the resistance of the lines.

5.8 Metallization stability

The metallization in test lines must be sufficiently stable so that when subjected to the stress temperature of the test (but not the stress current), no significant change will occur with time in the resistance of the individual test lines. Such changes would indicate a possible change in the crystallographic structure of the metallization that would impact sample estimates of t_{50} and sigma and give misleading characterizations if extrapolated to use conditions.

5.9 Lower limit on t_{50}

The method is applicable only when it is possible to measure $R(\mathrm{tl})_S$ of the test lines (8.6.3) before any measurable degradation due to electromigration has occurred and the time to do that is a small fraction of the sample estimate of t_{50}. See 2.6.

5.10 Normalization temperature

The normalization temperature, T_n, (4.3.3) can affect the accuracy of the sample estimates of t_{50} to the extent that T_n (8.8) is different from the mean of the metallization stress temperatures, T_m, and the extent that the estimate of the activation energy (4.3.7) is inaccurate.

5 Precautions and interferences (cont'd)

5.11 Test line geometry

When wishing to compare different metallizations of similar thickness by their sample estimates of t_{50} and sigma, the test lines involved shall have the same designed width and length. Otherwise, the possible dependence of t_{50} on line width and length will interfere with such comparisons (see 4.3.6).

5.12 Low-k dielectrics

When making measurements with test lines that involve low-k dielectrics, it is advisable to limit stress and ambient temperatures appropriately to avoid temperature-induced degradation of the dielectric material.

5.13 Standard probe-pad layout

A guide for standard probe pad sizes and layouts [8] was developed to facilitate and expedite wafer-level electrical testing. The use of such a guide provides for use of a minimum number of probe cards and card changes to accommodate the various test structures that may need to be tested. It also eases the conduct of inter-laboratory experiments used, for example, to evaluate test standards by a number of different organizations

5.14 Temperature range

Calculating values for $TCR(T)$ (6.2), dR/dT (6.3.2), R_θ (6.7), and $T(tl)_S$ (8.6.3) all involve using the difference of two temperatures or the difference of resistances measured at two temperatures. Because it is generally more difficult to make accurate temperature measurements than current and voltage, it is best to choose a conveniently large temperature range to minimize errors in determining the values listed above.

5.15 Convective heat loss

Because of convective and thermal heat losses, the top surface of a wafer will be at a slightly lower temperature than that of the top surface of the heated stage. This temperature difference will increase with increasing temperature of the heated stage. An added source of error in estimating the temperature of test lines in wafer-level testing is how the placement of a wafer probe card affects convective heat loss from the portion of the wafer that is being probed.

5.16 Degradation of thermocouple calibration

The calibration of a thermocouple installed in wafer-level testing stations to determine the temperature of the heated stage may degrade with long exposure to high temperatures. For this reason, it is wise to check the calibration of the thermocouple with a calibrated surface probe placed at various locations on the stage.

5 Precautions and interferences (cont'd)

5.17 Effect of vias on t_{50} and sigma

Test lines with vias and contacts are inherently more susceptible to electromigration-induced damage than are single-metal-level test structures for the same metallization design and treatment. Hence, t_{50} and other test-result data obtained from tests of single-metal-level test structures *shall not* be used to characterize the reliability of metallizations that include vias or contacts.

NOTE 1 Test lines with vias or contacts exhibit t_{50} values that are usually significantly *lower* than those values obtained from equivalent single-metal-level test lines -- for the same stress conditions and metallization.

NOTE 2 Electromigration stress tests of the latter structures are a test primarily of the extent to which the size, structure, and distribution of the grains in the test line create sites for metal-migration divergences that cause failure. For the former (via-type) structures, it is a test of not only the metal line between such vias and contacts but (additionally) of how much the conductor material interfaces, inherent in these structures, cause the metal-migration divergences that lead to failure.

6 Preparatory measurements

6.1 Elevated ambient temperature measurements

6.1.1 Wafer-level tests

Measure the surface temperature and its uniformity over the working area of the heated stage with a display resolution of 0.1 ˚C. This shall be done with a calibrated surface temperature probe at the temperatures to be used in the procedure: at T_L (8.2), at T_U (8.3.2), and at T_H (8.5.1). Record also the range of temperatures registered over a period of minutes at each elevated temperature to be used in the method to ensure that there is appropriate control of the temperature about each set point. (See 5.1 and 5.2.) Compare these surface temperatures with the temperature readings of the integral temperature sensor (e.g., thermocouple (see 5.16)) used to set the temperature of the heated stage. Repeat a portion of these measurements at temperatures T_U and T_H on the surface of a representative wafer on the heated stage (see 5.15). Document the results of these measurements and use them to determine the ambient temperatures of individual test lines during the procedure of the test.

6.1.2 Package-level tests

Measure the temperatures of representative packages in the oven at the elevated ambient temperatures to be used in the test with a display resolution of 0.1 ˚C. Record the range of temperatures registered over a period of minutes at each of the elevated temperatures to be used to ensure that there is appropriate control of the temperature. (See 5.1 and 5.2.) During these determinations, the loading (arrangements and configuration of packages) of the oven shall be similar to that used in the procedure of the test. Compare these readings with that of the sensor used to set the temperature of the oven. Document the results of these measurements and use them to determine the ambient temperatures of the test packages during the procedure of the test.

6 Preparatory measurements (cont'd)

6.2 Temperature coefficient of resistance

Determine the temperature coefficient of resistance, $TCR(T)$, to calculate the joule heating of the test structures due to the stress current used in the accelerated stress test. Use results of steps 6.2.1 *or* 6.2.2 in obtaining values for $TCR(T)$.

NOTE 1 If the measurement of the $TCR(T)$ of a copper-based line involves temperatures in excess of 200 ºC, then the corrections described in JESD33B (ref. 9) shall be used to account for the nonlinear dependence of the resistivity of copper with increasing temperature.

NOTE 2 The stress temperature of the test is the sum of ambient temperature and the increase in the temperature of the test line due to Joule heating.

6.2.1 Option A: Mean value for *TCR*(*T*)

Use JEDEC test standard JESD33B [9] to obtain $TCR(T_{ref})$ and $R(T_{ref})$ values from measurements of a representative sample of test structures. The reference temperature, T_{ref}, is a temperature somewhat above room temperature, but not necessarily equal to T_L of 8.2.1. Calculate the mean of $TCR(T_{ref})$ values and of the $TCR(T_{ref})\cdot R(T_{ref})$ products. Use these means in 8.4, where T_{ref} is a temperature somewhat above room temperature, but not necessarily equal to T_L of 8.2.1. Because the mean value for $TCR(T)$ has already been determined by the time the procedure is begun, there is no need to take steps 8.2 and 8.3 of the procedure.

NOTE 1 The product $TCR(T)\cdot R(T)$ is equal to the slope of the plot of resistance versus temperature and is dependent on the geometry of the test line. The $TCR(T)$ is independent of the geometry of the test line, but dependent on the residual resistivity of the conductor material.

NOTE 2 Equivalent test lines (same designed width and length) from the same wafer are expected to exhibit only small differences in $TCR(T)$ if all are processed so that the residual resistivity is uniform over the wafer. This may be true for such test lines on different wafers from the same lot, if the residual resistivity is unaffected by wafer order in the lot.

6.2.2 Option B: Individual values for *TCR*(*T*)

Use the test procedure (8.1 to 8.3) to obtain values for $TCR(T(\mathrm{tl})_L)$ and $R(T(\mathrm{tl})_L)$ of the individual test lines to be stressed. If equivalent test lines wish to be added to the test, whose low-temperature resistances have not been measured, then an appropriate estimate for the $TCR(T)$ of these test lines may be used in 8.6.3 to calculate the stress temperature of these lines. One such appropriate estimate may be to use the mean of the $TCR(T)$ values determined in 8.3.7 from the initial set of test lines.

6.3 Cross-sectional area

The cross-sectional areas of the primary and adjoining conductors are needed to calculate what stress current to use in order to achieve the current density stress in the primary conductor of the test line specified in 4.3.2. See also 6.4 regarding the assumptions about the adjoining conductor. One of the following two methods is to be used.

6.3 Cross-sectional area (cont'd)

6.3.1 From physical and other measurements

Estimate the mean cross-sectional areas of the primary and of any adjoining liner conductors from physical cross-sections of a representative sample of test lines and from experience with processing control of these areas. Stylus-type measurements to measure thickness and the use of cross-bridge test structures [10] to measure the electrical width of lines may be helpful to estimate these areas in aluminum based lines.

6.3.2 From electrical measurements

An estimate of the cross-sectional area of the primary conductor (aluminum or copper based) of a test line is obtained by an electrical method, assuming that Matthiessen's rule [11,12] holds for these two metals. Experimentally, the method requires only a measurement of dR/dT, the change in resistance of the test line with temperature, as may be obtained by resistance measurements near room temperature and a temperature approximately 100 ˚C above the lower temperature measurement (see 5.14). The following data will also be required: 1) the designed length of the test line, 2) the ratio of the cross-sectional *design* dimensions of the primary to that of the adjoining conductor films in the straight portion of the test line having constant cross-sectional area, and 3) the value for the change in resistivity with temperature of the pure, bulk form of the primary conductor (provided below for aluminum and copper) and an estimate of the same for the adjoining conductor. Ignoring the small affects of thermal expansion, the cross-sectional area of the primary conductor, A_P, is calculated from the following equation:

$$A_P = \frac{L}{dR/dT} \times (d\rho/dT)_{PB} \times \Phi/\Psi \ (cm^2), \tag{4}$$

where:

L is the length of the test line, defined by the separation of the voltage tap connections,

dR/dT is the change in resistance with temperature of the test line,

(dρ_P/dT)$_{PB}$ is the change in resistivity with temperature of the pure, bulk primary metal:

(dρ_P/dT)$_{PB}$ = 0.0115 · 10^{-6} Ω cm ˚C^{-1} for aluminum (ref. 9) and
(dρ_P/dT)$_{PB}$ = 0.00673 · 10^{-6} Ω cm ˚C^{-1} for copper (ref. 12),

$$\psi = 1 + \frac{\rho_P(T)}{\rho_a(T)} \times \frac{A_a}{A_P}, \ \Phi = 1 - \left(1 - \frac{1}{\psi}\right) \times \left(1 - \frac{\rho_P(T)}{\rho_a(T)} \times \frac{(d\rho_a/dT)_{PB}}{(d\rho_P/dT)_{PB}}\right),$$

A_P and A_a are the designed cross-sectional areas of the primary and adjoining conductors, respectively, and

ρ_P(T) and ρ_a(T) are the resistivities of the primary and adjoining conductors, respectively, which can be approximated here by their pure, bulk resistivities because the errors of doing so will not materially effect the calculated values of Ψ and Φ.

6.3 Cross-sectional area (cont'd)

6.3.2 From electrical measurements (cont'd)

For metallizations without any kind of adjoining conductor film, both Ψ and Φ are unity. For most realistic conditions where a liner does exist, these parameters will be only slightly different from unity. For example, if the primary metal is copper, the adjoining, barrier film is tantalum nitride (35 μΩcm), and $A_P/A_a = 0.29$; Ψ and Φ are 1.014 and 0.991, respectively.

Estimates of cross-sectional areas can be made directly for the lines to be tested if the resistances of the lines are measured at a moderately elevated temperature, as is done in Option B (6.2.2) of the test procedure in the process of determining a value for $TCR(T)$ for each test line to be stressed. If the test lines to be stressed have vias, the above equation can be used with minimal effect if the resistance of the via is less than a few percent of the total resistance of the test line. If this is not the case, a more complicated expression is needed.

6.4 Stress current

The stress current, I_C, through the aluminum- or copper-based primary conductor of the test line is equal to the product of the current-density stress selected in 4.3.2, J_{stress}, and the cross-sectional area, A_P, of the primary metal conductor of the test line in the region where the line is designed to be uniform. Hence, the total stress current will be the sum of this stress current and the current through any adjoining, electrically conducting film (see 2.3). This adjoining film is assumed to have an electrical resistivity, ρ_a, which is much greater than that of the primary metal, ρ_P, and to have a cross-sectional area, A_a, that is much smaller than that of the primary metal conductor. Hence, the total stress current, I_{stress} is expected to be only slightly larger than that through the core conductor and is given by

$$I_{stress} = I_P \times \left(1 + \frac{\rho_P(T)}{\rho_a(T)} \times \frac{A_a}{A_P} \right) = J_{stress} * A_P \times \psi \tag{5}$$

6.5 Microscopic inspection

Perform a microscopic inspection of the test structures to be stressed. Reject structures that are discontinuous or have other abnormal physical or other features. If structures are packaged but still accessible, ensure that the electrical wiring connecting the structures to the package terminals do not touch other connectors, or other parts of the chip or package.

6.6 Thermal response time of package

An estimate of the thermal response time of a representative test line shall be determined if the method is to be used on packaged test structures. The test structure shall be bonded in the package in the same manner as those that will be tested.

NOTE For packaged test lines, it may take several minutes before the test line will reach thermal equilibrium in the oven environment after a step increase in current to the stress level of the test that involves Joule heating. This thermal response time will be dependent on the package design.

6 Preparatory measurements (cont'd)

6.6 Thermal response time of package (cont'd)

6.6.1 With a *representative package* installed in an oven at a stable oven temperature, *measure the resistance of a test structure* bonded in the package with a test current, I_m, which is sufficiently small that no significant Joule heating is generated.

6.6.2 Select a *stress current* that will produce a conveniently measurable increase in the resistance of the packaged test line due to Joule heating.

6.6.3 *Switch on the stress current* and monitor the resistance continuously until the resistance is approximately constant.

6.6.4 The *thermal response time* shall be the time for the resistance of the test line to reach 90 % of its stable, Joule-heated state.

6.7 Thermal resistance

If a number of adjacent lying test lines on a wafer or in a package are to be stressed at the same time and if the stress current used generates Joule heating that elevates the temperature of a given test line by more than approximately 2 ˚C, then a thermal resistance should be determined to quantify the effect of any thermal communication among the test lines on a wafer or on a packaged chip. This thermal resistance can be measured with a number of test structures on a wafer or on a packaged chip representative of those that will be involved in the stress test. A determination of the mean value for $T(T_{ref}) \cdot TCR(T_{ref})$ (see 6.2) for these test lines will be needed as well as a determination of the thermal response time (see 6.6) of the packaged test lines.

6.7.1 Use an *ambient temperature* that is equal to the ambient stress temperature of the intended test or 180 ˚C, whichever is lower (see 5.12).

6.7.2 At this ambient temperature (6.7.1), *select a current, I_t*, that will produce a conveniently measurable temperature increase in a test line due to Joule heating.

6.7.3 *Measure $R(tl)_{Hs}$*, the resistance of a single test line among M lines with a current I_m that will generate negligible Joule heating (see 8.2.4). Then subject the same test line to current I_t and, after a delay, *measure its new resistance $R(tl)_{Ps}$*. The delay shall be one second for wafer-level measurements and 1.2 times the thermal response time of a packaged test line.

6.7.4 Calculate the *temperature increase* of the test line due to Joule heating in the single test line from:

$$\Delta T(s) = \frac{R(tl)_{Ps} - R(tl)_{Hs}}{R(T_{ref}) \times TCR(T_{ref})}$$

6 Preparatory measurements (cont'd)

6.7 Thermal resistance (cont'd)

6.7.5 Subject all M test lines to the same current I_t and, after a delay (see 6.7.3), measure and record the resistance of each line. Calculate ΔT(a), the change in temperature of the same single test line when all lines are stressed with I_t, using the change in resistance of this test line $\Delta R(tl)_S = R(tl)_{MPs} - R(tl)_{Hs}$, where $R(tl)_{MPs}$ is the resistance of the same single line when all M lines are powered.

$$\Delta T(a) = \frac{\Delta R(tl)_s}{R(T_{ref}) \times TCR(T_{ref})}$$

6.7.6 Calculate the *power dissipation* of each of the M test lines from the product of I_t^2 and the resistances recorded in 6.7.5. Calculate the mean of the M power dissipations and call it P_m

6.7.7 Calculate the *thermal resistance* R_θ from

$$R_\theta = \frac{\Delta T(a) - \Delta T(s)}{(M-1) \times P_m}$$

7 Electrical test system

To make the electrical measurements necessary in using the test method, the following capabilities are required of the test system.

7.1 Stress current control

The current through each test structure shall be individually adjustable to the current necessary to attain the desired current-density stress and be maintained constant during the stress test to within ± 0.2% of that current (see 5.1 and 5.2).

7.2 Display resolution

The voltage display resolution to determine the current through a test structure shall be at least 0.1% of the intended stress current (5.1). The display resolution of the voltage between the voltage taps of each test structure shall be equal to at least 0.1% of the display voltage before and during the stress test when used to make resistance measurement (5.1). When used to monitor for failure, as represented by a percent increase in resistance, the display resolution of the voltage shall be at least 10% of the voltage change induced by that percent change in resistance.

7.3 Maximum applied voltage

The maximum voltage applied across the test structure during the stress test, and including the time of failure, shall be less than the voltage where an open-circuit failure may self heal (see 5.6).

8 Procedure

8.1 Install test parts:

8.1.1 Wafer-level tests

Use a pressure-differential method to hold down the wafer (or part thereof) to the surface of the stage that is to be heated to the high-temperature stress of the test. See 6.1.1 regarding the temperature measurement and control of heated stage.

8.1.2 Package-level tests

Install packages in oven. See 6.1.2.

8.2 Measure the resistance of test lines at the lower temperature

If Option A (6.2.1) was selected, move ahead to 8.4.

8.2.1 *Set the temperature* of the heated stage or oven to temperature T_L. This temperature shall be a few degrees above any likely room temperature environment. (See 6.1 regarding temperature measurement and control.)

8.2.2 Insure that the test structures are in *thermal equilibrium* with the environment.

8.2.3 *For wafer-level measurements*, make electrical connections to the contact pads of the test structures to be stressed by an appropriate probe array. See 5.13 regarding standard probe-pad layout.

8.2.4 *Measure and store the resistance,* $R(tl)_L$, of each test line at temperature T_L using a current, I_m, that is sufficiently small to produce negligible joule heating. To determine if Joule heating is negligible, halve the current and remeasure the resistance. If no significant change in resistance is noted, the original current is acceptable.

8.2.5 *Raise probes* from the contact pads of all the test structures to be stressed (at the wafer level) after all test structures have been measured (8.2.3).

8.3 Determine $TCR(T_L)$ of the test lines to be measured

If Option A (6.2.1) was selected, move ahead to 8.4.

8.3.1 *Decision point:* If a mean value for the $TCR(T)$ has already been determined (6.2.1) and measurements of the change in resistance with temperature for each test line is not desired, go to 8.4. Otherwise, continue to 8.3.2.

8.3.2 *Increase the temperature* of the heated stage or oven to a temperature T_U, which is at least 60 ˚C above T_L and less than 200 ˚C. See 5.12 and 5.14.

8.3.3 Insure that the substrate is in *thermal equilibrium* with the environment.

8 Procedure (cont'd)

8.3 Determine $TCR(T_L)$ of the test lines to be measured (cont'd)

8.3.4 *For wafer-level measurements*, remake electrical connection to the contact pads of the test structures to be stressed by the probe array (8.2.3).

8.3.5 *Measure and store the resistance, $R(tl)_U$*, of each test line using current, I_m, (8.2.4)

8.3.6 *For wafer-level measurements*, withdraw probes from the contact pads after all test structures have been measured (8.3.5).

8.3.7 Calculate and store the *temperature coefficient of resistance* for each test structure at temperature T_L from:

$$TCR(T_L) = \frac{R(tl)_U - R(tl)_L}{R(tl)_L \times [T_U - T_L]}. \tag{6}$$

8.3.8 Calculate and store the *change in resistance with temperature* for each test line from:

$$\frac{dR(tl)}{d(T)} = \frac{R(tl)_U - R(tl)_L}{T_U - T_L}. \tag{7}$$

8.3.9 Calculate and store the *cross sectional area*, A_P, of the primary conductor of each test line with eq. 4, using the value calculated in 8.3.7, and the values from 6.3.2.

8.4 Calculate the stress current through each test structure

8.4.1 If *physical and other measurements* (6.3.1) were used to determine the cross-sectional areas A_P and A_a , use these values, the selected current density stress from 4.3.2, and estimates for the resistivity of the primary and adjoining conductor materials in eq. 5 to calculate the stress current to use in all involved test structures.

8.4.2 If *electrical measurements* (6.3.2, 8.3.8) were use to determine the cross-sectional area of the primary conductor, A_P, for individual test lines, use these values in eq. 5 to calculate and then store the stress current, I_{stress}, to be delivered to each test structure during the test. Equation 5 will also require the current-density stress selected in 4.3.2, the design value of A_a, and estimates for the resistivity of the primary and of the adjoining conductor materials (6.3.2).

8.5 Measure test line resistance $R(tl)_H$ at the high ambient stress temperature T_H

8.5.1 Increase the *temperature of the heated stage* or oven to the high ambient stress temperature, T_H, selected in 4.3.1.

8.5.2 Insure that the test lines are in *thermal equilibrium* with the heated environment.

8.5.3 *For wafer-level measurements*, make electrical connections to the contact pads of the test structures to be stressed by an appropriate probe array.

8.5.4 *Measure and store* the resistance, $R(tl)_H$, of each test line using current, I_m, (8.2.4)

8 Procedure (cont'd)

8.6 Initiate the stress test

8.6.1 *Set the timer to zero* and increase the current through each test line to the level determined in 8.4.1 or to the levels determined in 8.4.2, as appropriate.

8.6.2 *After a delay* of 1.2 times the package thermal response time determined in 6.6, or a delay of one second for wafer-level tests, measure and store the resistance, $R(\text{tl})_S$, of each test line.

8.6.3 Calculate and store the *stress temperature of each test line*, $T(\text{tl})_S$, using the following equation [9]:

$$T(tl)_S = F_{corr} \times T_{cal} = F_{corr} \times \left(\frac{R(tl)_S - R(tl)_H}{R(T) \times TCR(T)} + T_H \right) \tag{8}$$

where:

$R(T) \times TCR(T)$ is equal to $R(\text{tl})_L \times TCR(T_L)$ when individual values for $TCR(T)$ and $R(\text{tl})_L$ are determined as part of the above procedure (6.2.2), *or* is equal to the mean value for $R(\text{T}_{ref}) \times TCR(\text{T}_{ref})$ when step 6.2.1 is used (see 6.3.1),

$F_{corr} = 1.0$ for aluminum-based metallizations when $T_{cal} < 420$ ˚C and for copper-based metallizations when $T_{cal} \leq 200$ ˚C,

$F_{corr} = 1.0167 - 8.39751\ 10^{-5}\ T_{cal} - 3.74768\ 10^{-8}\ T^2_{cal}$ for copper-based metallizations when $T_{cal} > 200$ ºC, and

T_{cal} is given by the factor within the parentheses of eq. 8.

8.6.4 Calculate the *mean and standard deviation* of the stress temperatures, ($T(\text{tl})_S$), calculated in 8.6.3 and call them T_m and $SD(T_m)$, respectively.

8.7 Determine time to failure of each test line

8.7.1 Monitor the *voltage across each test line* at intervals that are less than 0.1% of the anticipated median time to failure.

8.7.2 *Record* the *first* time, t_n, that the voltage across a test line has indicated that the line has failed according to the failure criterion selected (4.3.4), and record the time, t_{n-1}, when the test line was last monitored (8.7.1).

8.7.3 Store the *estimated time to failure*, t, which is satisfactorily given by t_n if $t_n - t_{n-1} < 0.01 t_n$, otherwise use $t = \sqrt{t_n \times t_{n-1}}$.

8.7.4 *Reduce the current* to the failed test line to a negligible value after failure has been detected.

8.7.5 *Continue the stress test* until the failure times of all N lines on test have been recorded, or until the test is halted when time to failure of only K out of N lines have been recorded.

8 Procedure (cont'd)

8.8 Determine the mean stress temperature T_m of the test lines

8.8.1 *Decision:* If the tests were conducted on test lines that are individually packaged or tested individually on a wafer, proceed to 9.

8.8.2 *Stress temperatures for N lines:* For tests conducted on a number of adjacent lying test lines on a wafer or in a package and where the Joule heating of individual test lines are greater than approximately 2 ˚C, a thermal resistance, R_θ, will have been calculated (see 6.7). Calculate the stress temperature, $T_s(i)$, for each of the N test lines by using the following equations:

$T_S(1) = T_m$ where T_m was determined in 8.6.4,

and for $1 < M \leq N$

$$T_S(M) = T_m - \Delta T \times \left[(M-1) - \frac{\sum_{i=1}^{M-1} t_i}{t_M} \right]$$

and $\Delta T = P \cdot R_\theta$, where P is the mean of the power dissipations in the N test lines calculated from the product of the stress current and the resistance, $R(\text{tl})_S$ measured in 8.6.2. If the failure criterion is a percent increase in resistance, use the times at which the current to the failed test lines were reduced to a negligible value (8.7.4) if they differ significantly from the calculated failure times.

8.8.3 Calculate and store the *mean and standard deviation* of the stress temperatures, T_m, determined in 8.8.2 . (See 5.2.)

8.9 Verify if failure data can be modeled by a single log-Normal distribution

8.9.1 Calculate the *cumulative percent failure* of each test line in units of $1/(N+1)$, where N is the number of test lines stressed in the test. Other estimates of the median of the K-th smallest observation out of a sample of N from a standard Normal distribution may be used, e.g. see eq. 20 in reference 13.

8.9.2 Use a plot of the *failure-time data* on a logarithm scale versus a Normal probability scale of cumulative percent failed, or an equivalent plot, to verify that the points fall approximately along a straight line and thereby demonstrate that the data can be modeled by a well-behaved, log-Normal distribution.

NOTE Simulations of random samplings from a Normal distribution sometimes lead to plots that can be misleading.

8.9.3 Quantitative *tests for normality* are available, such as the Shapiro-Wilk Test, which has "consistently performed well" for complete data. [14]. Many statistical computer software packages are available that include this and other tests for normality. For Type II censored data, Lawless [14] has referred to a test by Tiku [15].

9 Analysis of *Complete* Time to Failure, *t*, Data

9.1 Calculate sample estimates of t_{50} and sigma

9.1.1 Calculate the sample estimate for the median time to failure, t_{50S}, from the mean of the logarithms of the failure times:

$$t_{50S} = \exp\left(\sum_{i}^{N} \ln t_i \;/\; N\right) = \exp\left[\left(\ln t\right)_{mean}\right]$$

9.1.2 Calculate t_{50sn}, the sample estimate of t_{50} normalized to stress temperature T_n (4.3.3), from t_{50s} (9.1.1) for the mean stress temperature, T_m, determined in 8.6.4 or 8.8.3 by using the following equation:

$$t_{50sn} = t_{50s}\ \exp\frac{E_a}{k}\left(\frac{1}{T_n} - \frac{1}{T_m}\right)$$

9.1.3 Calculate the sample estimate of sigma, s, from:

$$s = \sqrt{\frac{\sum_{i}^{N}\left(\ln t_i - \left(\ln t\right)_{mean}\right)^2}{N-1}}$$

9.2 Calculate confidence limits of t_{50} and sigma

9.2.1 Calculate the (1 – α) 100 % confidence limits for t_{50} from

$$t_{50S} \times \exp\left(\pm\, t\left(1-\alpha/2; N-1\right) \times s/\sqrt{N}\right)$$

where $t(1 - \alpha/2; N - 1)$ is the $(1 - \alpha/2)$ 100 percentile of the *t*-distribution for $N - 1$ degrees of freedom and sample size N.

NOTE If, for example, 90% confidence limits for t_{50} are desired, $t(0.95; N\text{-}1)$ is used.

9.2.2 Calculate the (1 – α) 100 percentile confidence limits for t_{50sn} (from 9.1.2) by multiplying the limits calculated in 9.2.1 by t_{50sn}/t_{50s}.

9.2.5 Calculate the $(1 - \alpha)$ 100 percentile confidence limits for sigma from:

$$s\sqrt{\frac{N-1}{\chi^2(1-\alpha/2; N-1)}} \quad \text{and} \quad s\sqrt{\frac{N-1}{\chi^2(\alpha/2; N-1)}}$$

where $\chi^2(1 - \alpha/2; \text{N-1})$ and $\chi^2(\alpha/2; N\text{-}1)$ are, respectively, the $1 - \alpha/2$ and $\alpha/2$ percentiles of the chi-squared distribution with N-1 degrees of freedom.

NOTE If 90 % confidence limits for sigma are desired: $\chi^2(0.95; N - 1)$ and $\chi^2(0.05; N - 1)$ would be used.

9 Analysis of *Complete* Time to Failure, *t*, Data (cont'd)

9.3 Calculate a sample estimate of t_p and its confidence limits

9.3.1 Calculate an estimate of the p-th percentile of the failure distribution from:

$t_{ps} = \exp\,[(\ln t)_{mean} + z_p\, s]$,

where z_p is the p-th percentile of the standard normal distribution.

NOTE For the 0.1 percentile of the distribution, $z_p = z(0.001) = -3.09$.

9.3.2 Calculate upper and lower $(1 - \alpha)$ 100 percentile confidence limits for t_p from:

$t_{ps} \exp\{s\,[z^+(l) - z_p]\}$ (upper limit)

$t_{ps} \exp\,\{s\,[z^+(u) - z_p]\}$ (lower limit)

NOTE The z^+ values are related to the noncentral *t*-distribution [16]. They can be obtained with acceptable accuracy (< 3% for N>10) from the following approximations [17].

where

$$z^+(u) = \frac{\left(z_p - \sqrt{z_p^{\;2} - A \times B}\right)}{A}$$

$$z^+(l) = \frac{\left(z_p + \sqrt{z_p^{\;2} - A \times B}\right)}{A}$$

and where

$$A = \left(1 - \frac{z(\alpha/2)^2}{2 \cdot (N-1)}\right) \quad \text{and} \quad B = \left(z_p^{\;2} - \frac{z(\alpha/2)^2}{N}\right)$$

Other methods giving equivalent or more accurate results may be used instead.

NOTE The confidence interval decreases with increasing sample size and with decreasing *s* much the same way as that for t_{50} except that the interval at a given sample size is considerably larger.

10 Analysis of singly, right-censored time to failure data

10.1 Calculate sample estimates of t_{50} and sigma

10.1.1 If the stress test was terminated before all test lines had failed, the approach of Persson and Rootzen, as modified by Lechner [18][19], is used to calculate the unbiased sample estimates of t_{50} and σ. The corrections for bias were obtained from simulations. It is assumed that the test is ended at time t_C, the time that K out of N parts on test have failed. If t_C is not equal to the time at which the K-th part failed, but later, then a small difference will be introduced in the calculated results. If desired, methods other than that described here may be used if they give equivalent or more accurate sample estimates and confidence intervals.

NOTE See JESD37 for details and an example. The standard makes use of the empirical work of J. A. Lechner [18].

10.1.2 Calculate unbiased sample estimate of sigma, $S_{\text{PR unbiased}}$, from

$$S_{PR\,unbiased} = \left(\frac{K}{K-1}\right)\times\left(\frac{1.8N+5}{1.8N+6}\right)\times S_{PR\,biased} = \left(\frac{K}{K-1}\right)\times\left(\frac{1.8N+5}{1.8N+6}\right)\times\sqrt{\frac{(K-1)sd^2}{K}+\alpha_{PR}(\alpha_{PR}-z_0)S^2_{RML}} \text{ where}$$

sd is the standard deviation of the K values of ln t,

z_0 is the standard normal value that corresponds to the (1-K/N) percentile of the standard normal distribution (e.g., if $N = 20$ and $K = 13$, $z_0 = -\,0.3854$.),

$$\alpha_{PR} = \frac{N}{K\sqrt{2\pi}}\exp-\left(\frac{z_0{}^2}{2}\right)$$

and

$$S_{RML} = \frac{1}{2}\times\left(z_0\times CM+\sqrt{z_0{}^2\times CM^2+4\times\left[CM^2+\left(\frac{K-1}{K}\right)\times sd^2\right]}\right)$$

where

$$CM = \ln t_C - (\ln t)_{mean(K)} = \ln t_C - \frac{1}{K}\sum_{i=1}^{K}\ln(t_i)$$

10.1.3 Calculate the unbiased sample estimate of the mean time to failure from the following

$$t_{50S} = \exp\{\ln t_{50S}\} = \exp\left\{\ln(t_{50S\,PRbiased})+\left[\frac{0.98}{K}+\frac{0.068N}{K^2}-\frac{1.15}{N}\right]\times S_{PRunbiased}\right\}$$

where

$$\ln(t_{50S\,PRbiased}) = (\ln t)_{mean(K)} + \alpha_{PR}\times S_{RML}\,.$$

10.1 Calculate sample estimates of t_{50} and sigma (cont'd)

10.1.4 Calculate the sample estimate of t_{50}, normalized to stress temperature T_n (4.3.3) by using the following equation:

$$t_{50sn} = t_{50s} \exp\frac{E_a}{k}\left(\frac{1}{T_n} - \frac{1}{T_m}\right).$$

10.2 Calculate approximate confidence limits of t_{50} and sigma

10.2.1 Calculate the approximate $(1 - \alpha)$ 100 % confidence limits for t_{50} (10.1.3) from

$$t_{50S} \times \exp\left(\pm z(1-\alpha/2) \times S_{PRunbiased} \times \sqrt{Var\{\ln t_{50S}\}} / \sqrt{N}\right)$$

where:

t_{50S} is the value determined in 10.1.3,
$S_{PRunbiased}$ is obtained from 10.1.2,

$Var\{ln\ t_{50S}\} = 6.0771 - 16.546\ (K/N) + 18.378\ (K/N)^2 - 6.9179\ (K/N)^3$ for $0.4 < K/N < 1.0$,
$Var\{ln\ t_{50S}\} = 1.0$ when $K/N = 1.0$
K is the number of failures recorded when the stress test was halted.

NOTE The confidence limits for t_{50} are obtained from using the normal-approximation method [3],[20 sect. 8.4] where the square root of $Var\{\ln t_{50S}\}$ is an inflation factor that reflects the effect of censoring on the confidence limits. The expression for $Var\{\ln t_{50S}\}$ is a fit to the data in column 6 of Table C.20 in reference 20, part of which is listed in Table B1 in ref. 3.

10.2.2 Calculate the approximate $(1 - \alpha)$ 100 % confidence limits for sigma from

$$S_{PRunbiased} \times \lambda_{s\pm}\left[1 \pm z(1-\alpha/2) \times \sqrt{Var\{s\}} / \sqrt{N}\right]$$

where:

$S_{PRunbiased}$ is obtained from 10.1.2,
$Var\{s\} = 4.4611 - 10.822\ (K/N) + 10.73\ (K/N)^2 - 3.8725\ (K/N)^3$
for $0.4 < K/N < 1.0$
$Var\{s\} = 0.5$ when $K/N = 1.0$ (no censoring)

And where

$$\lambda_{S+} = \frac{\sqrt{\dfrac{N-1}{\chi^2(\alpha/2, N-1)}}}{1 + z(1-\alpha/2) \times \sqrt{0.5}/\sqrt{20}} \quad \text{and} \quad \lambda_{S-} = \frac{\sqrt{\dfrac{N-1}{\chi^2(1-\alpha/2, N-1)}}}{1 - z(1-\alpha/2) \times \sqrt{0.5}/\sqrt{20}}$$

serve to normalize the confidence limits to those for complete data when $K = N$.

NOTE The confidence limits for sigma are obtained from using the normal-approximation method [3], [20 sect. 8.4] where the square root of $Var\{s\}$ is an inflation factor that reflects the effect of censoring on the confidence limits. The expression for $Var\{s\}$ is a fit to the data in column 7 of Table C.20 in reference [20], part of which is listed in Table B1 in ref. 3.

10.3 Calculate a sample estimate of t_p and its approximate confidence limits

10.3.1 Calculate an estimate of the p-th percentile of the failure distribution from:

$t_{ps} = \exp\,(ln\ t_{50S} + z_p\ S_{PRunbiased})$,

where: the values for t_{50s} and $S_{PRunbiased}$ are taken from 10.1.3 and 10.1.2, respectively, and z_p is the p-th percentile of the standard normal distribution.

NOTE For the 0.1 percentile of the distribution, $z_p = z(0.001) = -3.09$.

10.3.2 Calculate approximate $(1 - \alpha)$ 100% confidence limits for t_p from

$$t_{ps} \times \lambda_{p\pm} \times \exp\left(\pm S_{PRunbiased} \times z(1-\alpha/2) \times \sqrt{Var\{\ln_{50S} + z_p \times s\}} / \sqrt{N}\right)$$

where:
t_p is the value determined in 10.3.1,
$Var\{\ln t_{50S} + z_p \times s\} = Var\{ln\ t_{50S}\} + z_p^2 \times Var\{s\} + 2z_p \times Cov\{ln\ t_{50S}, s\}$,
$Var\{ln\ t_{50S}\} = 6.0771 - 16.546\ (K/N) + 18.378\ (K/N)^2 - 6.9179\ (K/N)^3$,
$Var\{s\} = 4.4611 - 10.822\ (K/N) + 10.73\ (K/N)^2 - 3.8725\ (K/N)^3$,
$Cov\{ln\ t_{50S}, s\} = 4.4498 - 13.455\ (K/N) + 14.455\ (K/N)^2 - 5.1583\ (K/N)3$
for $0.4 < K/N \leq 1.0$,
and $Var\{ln\ t_{50S} + z_p \times s\} = 1 + z_p^2 \times 0.5$ for $K/N = 1.0$.

And, where:

$$\lambda_{p+} = \frac{\exp\left(S_{PRunbiased} \times \left[z^+(l) - z_p\right]\right)}{\exp\left(S_{PRunbiased} \times z(1-\alpha/2) \times \sqrt{1 + z_p^{\ 2} \times 0.5} / \sqrt{N}\right)}$$

$$\lambda_{p-} = \frac{\exp\left(S_{PRunbiased} \times \left[z^+(u) - z_p\right]\right)}{\exp\left(-S_{PRunbiased} \times z(1-\alpha/2) \times \sqrt{1 + z_p^{\ 2} \times 0.5} / \sqrt{N}\right)}$$

serve to normalize the confidence limits to those for complete data when $K = N$.

NOTE The confidence limits for p-th percentile are obtained from using the normal-approximation method [3], [20, sect. 8.4] where the square root of $Var\{ln\ t_{50S} + z_p \times s\}$ is an inflation factor that reflects the effect of censoring on the confidence limits. The expression for $Var\{ln\ t_{50S} + z_p \times s\}$ is a fit to the data in column 8 of Table C.20 in reference [20], part of which is listed in Table B1 in ref. 3.

11 Required Reporting

11.1 Test structure description

11.1.1 A representational illustration or description of the test structure design.

11.1.2 Metal and estimated resistivity (at a specified temperature) of primary and any adjoining conductors (3.1).

11.1.3 Design length, width, and thickness of straight-line portion of test line (3.2, 4.3.6).

11.1.4 Estimated cross-sectional area of primary and any adjoining conductor comprising the test line and any vias (6.3).

11.2 Test option, conditions, and results

11.2.1 Test option used (4.2).

11.2.2 Mean ambient stress (4.3.1), mean stress, T_m (8.8), and normalization stress T_n, temperatures.

11.2.3 Mean current-density stress in primary conductor (4.3.2, 8.4).

11.2.4 Number, N, of test structures on test (4.3.5) and number, K, (9.3.1) of failures analyzed.

11.2.5 Failure criterion (4.3.4).

11.2.6 Sample estimates of t_{50sn} and s, with confidence limits (9.2.6, 9.2.7, or 9.3.4).

12 References

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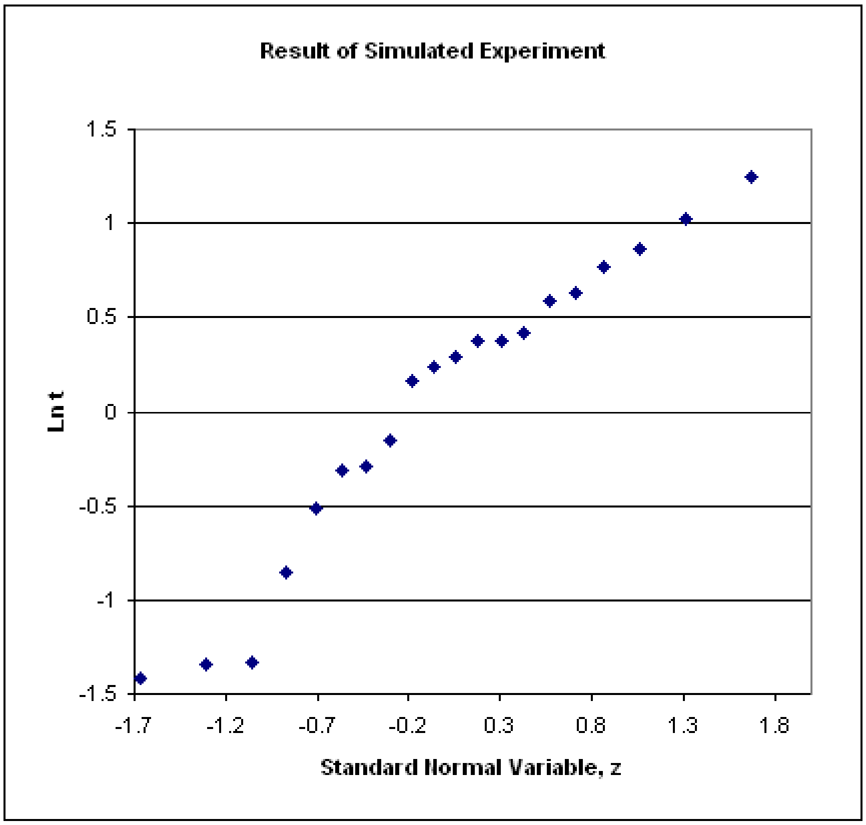
Annex A Sample Calculations Involved in Sections 9 and 10

A.1 Simulated experiment

An experiment is simulated in which 20 parts are placed on a stress test.

From a table of random standard normal numbers, a set of 20 consecutive values were selected and used to represent the logarithms of 20 failure times, t, drawn from a Normal distribution N(0,1) with a mean of zero (ln $t_{50} = 0$) and a sigma of one ($\sigma = 1.0$). To provide sample calculations for censored data, it is assumed that the experiment was halted at a time, t_C, after 13 parts had failed, i.e. where ln $t_C = 0.4$. The 20 values for ln t_i are listed below in ascending order along with their standard normal variables, $z(i/(N+1)) = z(i/21)$. These points are plotted in the adjoining figure

X = z	Y = ln t
-1.67	-1.42
-1.31	-1.346
-1.06	-1.334
-0.87	-0.853
-0.71	-0.513
-0.565	-0.309
-0.43	-0.287
-0.305	-0.151
-0.18	0.161
-0.06	0.235
0.06	0.292
0.18	0.375
0.305	0.375
0.43	0.424
0.565	0.593
0.71	0.63
0.87	0.768
1.06	0.862
1.31	1.026
1.67	1.25



The 90% confidence ($1-\alpha = 0.9$) limits for t_{50}, sigma, and the 0.1-th percentile of the failure distribution, $t_{0.1}$, are calculated. Hence, $z_p = z(0.001) = -3.09$. In the analysis of censored data: $N = 20$, $K = 13$, and ln $t_C = 0.4$. The average and the standard deviation for the complete data and for the censored data are, respectively:

Complete Data: $(\ln t)_{mean} = 0.0389$ and s = 0.797789.
Censored Data: $(\ln t)_{mean(K)} = -0.367308$ and sd = 0.676564.

A2 Calculations of quantities found in subclauses of 9 (Analysis of complete time to failure, t, data)

A.2.1 Calculate the sample estimate for the median time to failure, t_{50S}

$$t_{50S} = \exp\left(\sum_i^N \ln t_i \; / \; N\right) = \exp[(\ln t)_{mean}] = \exp\ 0.0389 = 1.03967.$$

NOTE The data come from a distribution where the mean is zero and the standard deviation is one.

A.2.2 Calculate the sample estimate of sigma, *s*

$$s = \sqrt{\frac{\sum_i^N \left(\ln t_i - (\ln t)_{mean}\right)^2}{N-1}} = 0.797789\,.$$

A.2.3 Calculate the 90 % confidence limits for t_{50}

$$t_{50S} \times \exp\left(\pm\, t(1-\alpha/2; N-1) \times s/\sqrt{N}\right) = t_{50S} \times \exp\left(\pm\, t(0.95;19) \times 0.797789/\sqrt{20}\right)$$

and

$$t_{50S} \times \exp\left(\pm 1.729 \times 0.797789/\sqrt{20}\right) = t_{50S} \times \exp \pm 0.30844\,.$$

Hence, $0.7346\ t_{50S} \le t_{50} \le 1.3613\ t_{50S}$ and $0.7637 \le t_{50} \le 1.4153$.

A.2.4 Calculate the 90 % confidence limits for sigma

$$s\sqrt{\frac{N-1}{\chi^2(1-\alpha/2; N-1)}} \quad \text{and} \quad s\sqrt{\frac{N-1}{\chi^2(\alpha/2; N-1)}}$$

$$s\sqrt{\frac{19}{\chi^2(0.95,19)}} = s\sqrt{\frac{19}{30.14}} = s \times 0.793972 = 0.633422 \quad \text{and}$$

$$s\sqrt{\frac{19}{\chi^2(0.05,19)}} = s\sqrt{\frac{19}{10.12}} = s \times 1.37021 = 1.09314\,.$$

Hence: $0.7940\ s \le \sigma \le 1.3702\ s$ and $0.6334 \le \sigma \le 1.0931$.

A.2.5 Calculate an estimate of the 0.1-th percentile of the failure distribution

$t_{0.1s} = \exp[(\ln t)_{mean} + z_{0.1}\, s] = \exp[\, 0.0389 + (-3.09)\ 0.797789] = \exp -2.42627$

$t_{0.1s} = 0.088366$

NOTE The parent distribution: $t_{0.1} = \exp(0 - 3.09) = 0.045502$,

A2 Calculations of quantities found in subclauses of 9 (Analysis of complete time to failure, t, data) (cont'd)

A.2.6 Calculate upper and lower 90 % confidence limits for $t_{0.1}$.

Upper limit:
$t_{0.1s}\exp\{s\,[z^{+}(l)-z_{0.1}]\} = t_{0.1s}\exp\{0.72945\,s\} = 1.78952\ t_{0.1s} = 0.15813$

Lower limit:
$t_{0.1s}\exp\{s\,[z^{+}(u)-z_{0.1}]\} = t_{0.1s}\exp\{-1.20327s\} = 0.38291\ t_{0.1s} = 0.03384$

Rewriting: $0.38291\ t_{0.1s} \le t_{0.1} \le 1.78952\ t_{0.1s}$ and $0.03384 \le t_{0.1} \le 0.158133$

NOTE $t_{0.1} = 0.045502$ for the parent distribution.

$$z^{+}(u)=\frac{\left(z_{0.1}-\sqrt{z_{0.1}{}^{2}-A\times B}\right)}{A}=-4.29327$$

$$z^{+}(l)=\frac{\left(z_{0.1}+\sqrt{z_{0.1}{}^{2}-A\times B}\right)}{A}=-2.36055$$

$$A=\left(1-\frac{z(\alpha/2)^{2}}{2\times(N-1)}\right)=\left(1-\frac{(-1.645)^{2}}{2\times 19}\right)=0.92879 \quad \text{and}$$

$$B=\left(z_{0.1}{}^{2}-\frac{z(\alpha/2)^{2}}{N}\right)=\left((-3.09)^{2}-\frac{(-1.645)^{2}}{20}\right)=9.4128$$

A.3 Calculation of quantities found n subclauses of 10 (Analysis of singly, right-censored time to failure data)

A.3.1 Calculate unbiased sample estimate of sigma, $S_{PR\ unbiased}$

$$S_{PR\,unbiased}=\left(\frac{K}{K-1}\right)\times\left(\frac{1.8N+5}{1.8N+6}\right)\times S_{PR\,biased}=\left(\frac{K}{K-1}\right)\times\left(\frac{1.8N+5}{1.8N+6}\right)\times\sqrt{\frac{(K-1)sd^{2}}{K}+\alpha_{PR}(\alpha_{PR}-z_{0})S^{2}{}_{RML}}$$

$S_{PRunbiased} = 1.05754 \cdot 0.91279 = 0.96531$

where:
$sd = 0.676564$

$z_0(1\text{-}K/N) = z_0(0.35) = \text{-}0.3854$ $\quad \alpha_{PR}=\dfrac{N}{K\sqrt{2\pi}}\exp-\left(\dfrac{z_0{}^{2}}{2}\right)=\dfrac{20}{13\sqrt{2\pi}}\exp\dfrac{-(-0.3854)^{2}}{2}=0.56983$

$$S_{RML}=\frac{1}{2}\times\left(z_0\times CM+\sqrt{z_0{}^{2}\times CM^{2}+4\times\left[CM^{2}+\left(\frac{K-1}{K}\right)\times sd^{2}\right]}\right)=0.868581$$

$$CM=\ln t_C-(\ln t)_{mean(K)}=\ln t_C-\frac{1}{K}\sum_{i=1}^{K}\ln(t_i)=0.4-(-0.36731)=0.76731$$

A.3 Calculation of quantities found n subclauses of 10 (Analysis of singly, right-censored time to failure data) (cont'd)

A.3.2 Calculate the sample estimate of the mean time to failure

$$t_{50S} = \exp\{\ln t_{50S}\} = \exp\left\{\ln(t_{50S\,PRbiased}) + \left[\frac{0.98}{K} + \frac{0.068N}{K^2} - \frac{1.15}{N}\right] \times S_{PRunbiased}\right\}$$

$$t_{50S} = \exp\{\ln t_{50S}\} = \exp\left\{0.12763 + \left[\frac{0.98}{13} + \frac{0.068 \times 20}{13^2} - \frac{1.15}{20}\right] \times 0.96531\right\} = \exp 0.15266 = 1.1649$$

where,

$$\ln(t_{50S\,PRbiased}) = (\ln t)_{mean(K)} + \alpha_{PR} \times S_{RML} = -0.36731 + 0.56983 \times 0.868581 = 0.12763.$$

A.3.3 Calculate the approximate 90 % confidence limits for t_{50}

$$t_{50S} \times \exp\left(\pm z(0.95) \times S_{PRunbiased} \times \sqrt{Var\{\ln t_{50S}\}} / \sqrt{N}\right)$$

$$t_{50S} \times \exp\left(\pm 1.645 \times 0.96531 \times \sqrt{1.1871} / \sqrt{20}\right) = t_{50S} \times \exp \pm 0.38687 = 1.4724\, t_{50S};\ 0.6792\, t_{50S}$$

Hence, $0.6792\ t_{50S} \leq t_{50} \leq 1.4724\ t_{50S}$ and $0.7912 \leq t_{50} \leq 1.7152$

where:
$t_{50S} = 1.1649$
$S_{PRunbiased} = 0.96531$
$Var\{\ln t_{50S}\} = 6.0771 - 16.546\ (K/N) + 18.378\ (K/N)^2 - 6.9179\ (K/N)^3 = 1.1871$
for $K/N = 13/20 = 0.65$
$Var\{\ln t_{50S}\} = 1.0$ when $K/N = 1.0$ (no censoring)

A.3.4 Calculate the approximate 90 % confidence limits for sigma

$$S_{PRunbiased} \times \lambda_{s\pm} [1 \pm z(1-\alpha/2) \times \sqrt{Var\{s\}} / \sqrt{N}\ ]$$

upper bound: $S_{PRunbiased} \times 1.0874 \times [1 + 1.645 \times \sqrt{0.89674} / \sqrt{20}\ ]$

lower bound: $S_{PRunbiased} \times 1.0731 \times [1 - 0.34832]$

and, $0.6993\ S_{PRunbiased} \leq \sigma \leq 1.4662\ S_{PRunbiased}$ and $0.6750 \leq \sigma \leq 1.4153$

where:
$S_{PRunbiased} = 0.96531$
$Var\{s\} = 4.4611 - 10.822\ (K/N) + 10.73\ (K/N)^2 - 3.8725\ (K/N)^3 = 0.89674$
for $K/N = 13/20 = 0.65.$
$Var\{s\} = 0.5$ when $K/N = 1.0$ (no censoring)

A.3 Calculation of quantities found n subclauses of 10 (Analysis of singly, right-censored time to failure data) (cont'd)

A.3.4 Calculate the approximate 90 % confidence limits for sigma (cont'd)

And, where:

$$\lambda_{s+} = \frac{\sqrt{\dfrac{N-1}{\chi^2(\alpha/2, N-1)}}}{1+z(1-\alpha/2)\times\sqrt{0.5}/\sqrt{N}} = \frac{\sqrt{\dfrac{19}{\chi^2(0.05,19)}}}{1+z(0.95)/\sqrt{40}} = \frac{\sqrt{\dfrac{19}{10.12}}}{1+1.645/\sqrt{40}} = 1.0874$$

$$\lambda_{s-} = \frac{\sqrt{\dfrac{N-1}{\chi^2(1-\alpha/2, N-1)}}}{1-z(1-\alpha/2)\times\sqrt{0.5}/\sqrt{N}} = \frac{\sqrt{\dfrac{19}{\chi^2(0.95,19)}}}{1-z(0.95)/\sqrt{40}} = \frac{\sqrt{\dfrac{19}{30.14}}}{1-1.645/\sqrt{40}} = 1.0731$$

A.3.5 Calculate an estimate of the 0.1-th percentile of the failure distribution

$t_{0.1s} = \exp(\mathit{ln}\ t_{50S} + z_{0.1}\ S_{PRunbiased}) = \exp(0.15266 - 3.09 \times 0.96531) = 0.05901$

A.3.6 Calculate approximate 90% confidence limits for $t_{0.1}$

$$t_{0.1s} \times \lambda_{0.1\pm} \times \exp[\pm S_{PRunbiased} \times z(1-\alpha/2) \times \sqrt{Var\{\ln t_{50S} + z_{0.1} \times s\}}/\sqrt{N}\ ]$$

upper limit: $t_{0.1s} \times 0.8615 \times \exp[0.9653 \times 1.645\sqrt{7.3101}/\sqrt{20}\ ] = 2.2500 \times t_{0.1s}$

lower limit: $t_{0.1s} \times 0.7347 \times \exp[-0.9653 \times 1.645\sqrt{7.3101}/\sqrt{20}\ ] = 0.2813 \times t_{0.1s}$ so,

$0.2813\ t_{0.1s} \leq t_{0.1} \leq 2.2500\ t_{0.1s}$ and $0.0166 \leq t_{0.1} \leq 0.1328$

where:

$t_{0.1s} = 0.0590$

$Var\{ln\ t_{50S} + z_{0.1} \times s\} = Var\{ln\ t_{50S}\} + z_{0.1}{}^2 \times Var\{s\} + 2z_{0.1} \times Cov\{ln\ t_{50S}, s\}$,

$Var\{ln\ t_{50S} + z_{0.1} \times s\} = 1.1871 + 3.09^2 \times 0.89674 - 6.18 \times 0.3947 = 7.3101$

For $K/N = 13/20 = 0.65$:

$Var\{ln\ t_{50S}\} = 6.0771 - 16.546\ (K/N) + 18.378\ (K/N)^2 - 6.9179\ (K/N)^3 = 1.1871$,

$Var\{s\} = 4.4611 - 10.822\ (K/N) + 10.73\ (K/N)^2 - 3.8725\ (K/N)^3 = 0.89674$

$Cov\{ln\ t_{50S}, s\} = 4.4498 - 13.455\ (K/N) + 14.455\ (K/N)^2 - 5.1583\ (K/N)^3 = 0.3947$

For $K/N = 1$: $Var\{ln\ t_{50S} + z_{0.1} \times s\} = 1 + z_{0.1}{}^2 \times 0.5$ (no censoring)

$$\lambda_{0.1+} = \frac{\exp\left(S_{PRunbiased} \times [z^+(l) - z_{0.1}]\right)}{\exp\left(S_{PRunbiased} \times z(0.95)\sqrt{1+0.5\, z_{0.1}{}^2}/\sqrt{N}\right)} = \frac{\exp(0.9653 \times [-2.36055 + 3.09])}{\exp\left(0.9653 \times 1.645\sqrt{1+3.09^2/2}/\sqrt{20}\right)} = 0.8615$$

$$\lambda_{0.1-} = \frac{\exp\ (S_{PRunbiased} \times [z^+(u) - z_{0.1}])}{\exp\left(-S_{PRunbiased} \times z(0.95)\sqrt{1+0.5\, z_{0.1}{}^2}/\sqrt{N}\right)} = \frac{\exp(0.9653 \times [-4.29327 + 3.09]))}{\exp\left(-0.9653 \times 1.645\sqrt{1+3.09^2/2}/\sqrt{20}\right)} = 0.7347$$

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