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A Procedure for Performing SWEAT

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1 Scope

This document describes an algorithm for performing the Standard Wafer Level Electromigration Accelerated Test (SWEAT) method with computer controlled instrumentation. The algorithm requires a separate iterative technique (not provided) to calculate the force current for a given target time to failure.

This document does not specify what test structure to use with this procedure. However, users of this algorithm report its effectiveness on both straight-lines and via-terminated test structures. Some test-structures design features are provided in JESD87 and in ASTM 1259M - 96.

2 Introduction

The SWEAT method is an accelerated electromigration test performed on microelectronic metallizations. This highly accelerated test was developed as a method for obtaining quickly a measure of metallization reliability and for providing process control data to the semiconductor manufacturer.

This document presents an algorithm for performing the SWEAT method with computer controlled instrumentation. The algorithm is derived from published and unpublished literature. It provides little innovation beyond what is currently documented. The intent is to provide a complete description of a basic, functional, SWEAT algorithm that will facilitate software development and the use of highly accelerated stress testing.

The SWEAT algorithm uses a feedback control loop to adjust the stress current applied to the metallization under test. Using Black's equation, the stress current is adjusted such that the temperature and current density of the structure maintain the estimated time to failure within an error band of the selected target value.

3 Applicable documents

Root, B. and Turner, T., *Wafer Level Electromigration Tests for Production Monitoring*, IEEE/International Reliability Physics Symposium, 1985, pp. 100-107.

Von Hagen, J., Antonin, G., Fazekas, J., Head, L., and Schafft, H., *New SWEAT Method for Fast, Accurate and Stable Electromigration Testing on Wafer Level*, IEEE/Integrated Reliability Workshop, Final Report, 2000, pp. 85-89.

Zitzelsberger, A., Bauer, R., Von Hagen, J., Lepper, M., and Pietsch, A., *Electromigration Testing on Via Line Structures with Fast Wafer Level Tests in Comparison to Standard Package Level Tests*, IEEE/International Interconnect Technology Conference, Final Report, 2000, pp. 180-182.

3 Applicable documents (cont'd)

JEDEC Standard JESD33A, *Standard Method for Measuring and Using the Temperature Coefficient of Resistance to Determine the Temperature of a Metallization Line*.

JEDEC Standard JESD37, *Standard for Log normal Analysis of Uncensored Data, and of Singly Right-Censored Data Utilizing the Persson and Rootzen Method*.

JEDEC Standard JESD61, *Isothermal Electromigration Test Procedure*.

EIA/JEDEC Standard EIA/JESD63, *Standard Method for Calculating the Electromigration Model Parameters for Current Density and Temperature*.

JEDEC Standard JESD87, *Standard Test Structures for Reliability Assessment of AlCu Metallization with Barrier Materials*.

ASTM 1259M-96, *Standard Guide for Design of Flat, Straight-Line Test Structures for Detecting Metallization Open-Circuit or Resistance-Increase Failure Due to Electromigration.*

4 Terms and definitions

4.1 estimated time to failure (t_{FE}) {s}

The time it takes for the combined stress of temperature and current density to result in a prescribed increase in resistance of the test structure (definition of failure) as determined from Black's equation[1].

$$t_{FE} = A \cdot J^{-n} \cdot e^{E_a / kT} \quad (1)$$

where: A is an empirically determined constant, provided by the user

J is the current density (A/cm^2).

n is the current density factor, provided by the user
(value of 2 is often used, but larger or smaller values have been reported.)

E_a is the activation energy of the metallization, provided by the user (e*V*).

k is Boltzmann's constant (8.62E-5 e*V*/K), and.

T is the mean temperature of the test structure (K).

[1] BLACK, S. R., *Electromigration of Al-Au Alloy Films*, Proc: International Reliability Physics Symposium, 1978, pp. 233-240.

4 Terms and definitions (cont'd)

4.2 failure resistance criterion (R_{FC}) {Ω}

The resistance at or above which the test structure is considered to have failed.

NOTE It is equal to the product of the resistance of the test structure at the end of the initial settling period and a preselected fractional increase in resistance.

4.3 resistance at chuck temperature (R_{CT}) {Ω}

The resistance of the test structure at the wafer chuck temperature, T_{CT}, before the test structure is subjected to joule heating in accordance with the SWEAT algorithm.

4.4 chuck temperature (T_{CT}) {°C}

The metallization temperature at the time R_{CT} is measured; this is the temperature of the structure before joule heating.

4.5 temperature coefficient of resistance [TCR(T_{ref})] {°C^{-1}}

The fractional change in resistance of the test structure per unit change in temperature at a specified temperature, T_{ref}, as described in the following equation:

$$\mathrm{TCR}(T_{\mathrm{ref}}) = \frac{1}{R(T_{\mathrm{ref}})} \cdot \frac{\Delta R}{\Delta T} \tag{2}$$

NOTE For aluminum alloy metallizations, the change in resistance of the test structure with temperature is approximately constant from room temperature to about 420 °C. For copper alloy metallizations, a change in $\Delta R/\Delta T$ becomes evident at temperatures as low as 230 °C. Hence, if TCR(T_{ref}) is to be used to calculate the temperature of copper test structure at higher temperatures, a correction factor, F_{corr} will be required (see 6.2.2 and 7.6).

4.6 thermal resistance (R_{th}) {°C/W}

The change in mean temperature of the test structure divided by the change in the power dissipation ($I^2_{frc} \times R(T)$) that causes the temperature increase in the structure.

$$R_{\mathrm{th}} = {\Delta T}/{\Delta P} \tag{3}$$

NOTE R_{th} is dependent on the geometry of the test structure and on the thermal conductance to the ambient, which is temperature dependent (see 7.7). In a plot of T versus P, the thermal resistance is the slope of the curve. Because the thermal conductance of the materials in the path of the heat flow from the test structure is temperature dependent, the slope will gradually change with increasing power dissipation. However, the thermal resistance can be regarded as a constant over the limited range of temperatures experienced by the test structure after the stress temperature has been attained. It is assumed that the change in resistance of the test structure due to electromigration does not, to the first order, affect its thermal resistance.

4 Terms and definitions (cont'd)

4.7 target time to failure (t_{FT}) {s}

The desired time it should take for the resistance of the test structure to first equal or exceed the failure resistance criterion, R_{FC}, while the structure is under stress from the SWEAT algorithm.

4.8 starting current density (J_S) {A/cm²}

The current density in the narrowest region of the test structure at the initial application of the forcing current, I_{frc}.

NOTE The current density is calculated using area, *a*.

4.9 forced current (I_{frc}) {A}

The current that is forced through the test structure. See 6.2.3, 6.2.5, and 6.2.7.

4.10 area (*a*) {cm²}

The cross-sectional area of the narrowest region of the test structure.

4.11 error band (B_E) {s}

The band centered around the target time to failure, t_{FT}, within which the SWEAT algorithm will not permit the feedback control loop to adjust the forcing current, and whose boundaries ($t_{FT} + B_E$ and $t_{FT} - B_E$) constitute the limits for the estimated time to failure, t_{FT}, where B_E is half the width of the error band

$$t_{FT} - B_E < t_{FE} < t_{FT} + B_E \tag{4}$$

4.12 time to failure (t_F) {s}

The time it takes for the resistance of the test structure to first equal or exceed the failure resistance criterion, R_{FC}, while the structure is under stress from the SWEAT algorithm.

4.13 resistance at failure (R_F) {Ω}

The value of the last recorded resistance of the test structure during the control cycle before the failure criterion, R_{FC}, is satisfied.

4.14 current density at failure (J_F) {A/cm²}

The value of the last recorded current density in the narrowest region of the test structure during the control cycle before the failure criterion, R_{FC}, is satisfied.

NOTE The current density is calculated using area, *a*.

4 Terms and definitions (cont'd)

4.15 temperature at failure (T_F) {°C}

The value of the last recorded estimated mean temperature of the test structure during the control cycle before the failure criterion, R_{FC}, is satisfied.

5 Technical requirements

5.1 Equipment requirements

a) A programmable current source capable of supplying sufficient current density to accelerate the electromigration failure of the metallization. Typically, a current density of approximately 10^7 A/cm² or higher is sufficient. Minimum current force resolution of 12 bits, or 3.5 digits is recommended.

b) A digital voltmeter capable of measuring the expected voltage magnitudes. Typically 10 volts or higher is sufficient. See 6.1.1 for considerations in the selection of the current-density stress. Minimum measurement resolution of 12 bits, or 3.5 digits is recommended.

c) A computer controller. The computer provides a feedback control system. It controls the current to the metallization under test, based on voltmeter readings and computations directed by the SWEAT algorithm at discrete times.

5.2 General system recommendations

The system should be capable of executing a control cycle in a time shorter than 1% of the target time to failure. The intent is to keep the time to measure the estimated fail time to less than 1% of the actual time to failure. See 6.1.1 for more on the feedback control time. The system should also provide sufficient feedback for effective control.

5.3 Test configuration

Due to the required accuracy for the voltage measurement, four-wire Kelvin connection to the structure is required. Depending on the test structure and stress conditions, a high current may need to be applied. The connections to the test structure must be able to sustain this current.

6 The SWEAT algorithm

6.1 Description of SWEAT

The SWEAT method uses a feedback control loop to adjust the stress current applied to the metallization such that temperature and current density of the structure maintain the target time to failure within a programmed error band. Figures 1 and 2 illustrate the feedback control loop for computer controlled instrumentation.

Current is forced through the structure to achieve and then maintain the estimated time to failure, t_{FE}, within the error band B_E of the target time to failure, t_{FT}.

The first current level for the ramp-up stage is calculated from Black's Equation by using a starting target time to failure much longer (e.g., 100x) than the desired one. The reason is that the current should be high enough to obtain an adequately short settling time, but not so high that the structure will be overstressed. Refer to 6.1.1. This starting target time to failure is decreased monotonically until the estimated target time to failure falls within the error band of the target time to failure. The duration of this process of the feedback control loop is called the initial settling period, or ramp-up phase. During this phase, the structure's temperature is determined by using the TCR-relation of equation 6 (6.2.2). The power dissipation is calculated at each temperature determination and the values for P and T are stored. After an increase of approximately 50 °C, the stored values of P and T are used to calculate an initial value for R_{th} from equation 9 (6.2.4). With each subsequent adjustment of the forcing current, the new values for P and T are determined, stored, and a new value for R_{th} is calculated using P and T data pairs, where T is within approximately 50 °C of the maximum measured value for T. At the end of the settling period, the most recently determined value for R_{th} is used thereafter to determine the stress temperature of the test structure from the most recently determined value for the power dissipation during the stress phase.

Immediately upon completion of the initial settling period, the failure resistance R_{FC} is computed by multiplying the structure resistance by the fractional increase in resistance selected to be the failure criterion, as indicated in Figure 2.

After the initial settling period, the feedback control algorithm adjusts the current in order to maintain the estimated time to failure within the allowed error band as electromigration changes the resistance of the structure. Finally, the resistance of the test structure will exceed the failure resistance. This is reflected, through the estimation of structure temperature, as a rapid decrease in the estimated time to failure. The test is then terminated and the results are logged.

6.1.1 SWEAT characteristics

The typical characteristics of the initial settling period applied during this test can be as follows:

Settling period

Less than or equal to 10 percent of the target time to failure or at least one second. Settling period of less than one second may cause t_{FE} to overshoot t_{FT}, overstressing the structure and invalidating the test.

6.1 Description of SWEAT (cont'd)

6.1.1 SWEAT characteristics (cont'd)

Estimated time to failure t_{FE}

Must not be less than the target time to failure during the initial settling time to prevent overstress of the structure

Typical current density range

1.E+7 to 3.E+7 A/cm². The current density required will depend on a number of considerations: the thermal resistance of the line, the metallization and its susceptibility to electromigration, and the target fail time. For example, wider lines will generally need a smaller current-density stress than narrower lines for a given target failure time, and to achieve shorter target fail times will require larger current-density stresses.

Feedback control time

The feedback control time is the sum of the response time of the current source, the time to make the measurements and to perform the computations, and a delay time. A delay time is added to prevent a voltage measurement before any change in the forcing current has been completed. The delay must not be so long that the feedback control cannot adequately monitor the conditions of the test structure. See also interferences in 7.2.

6 The SWEAT algorithm (cont'd)

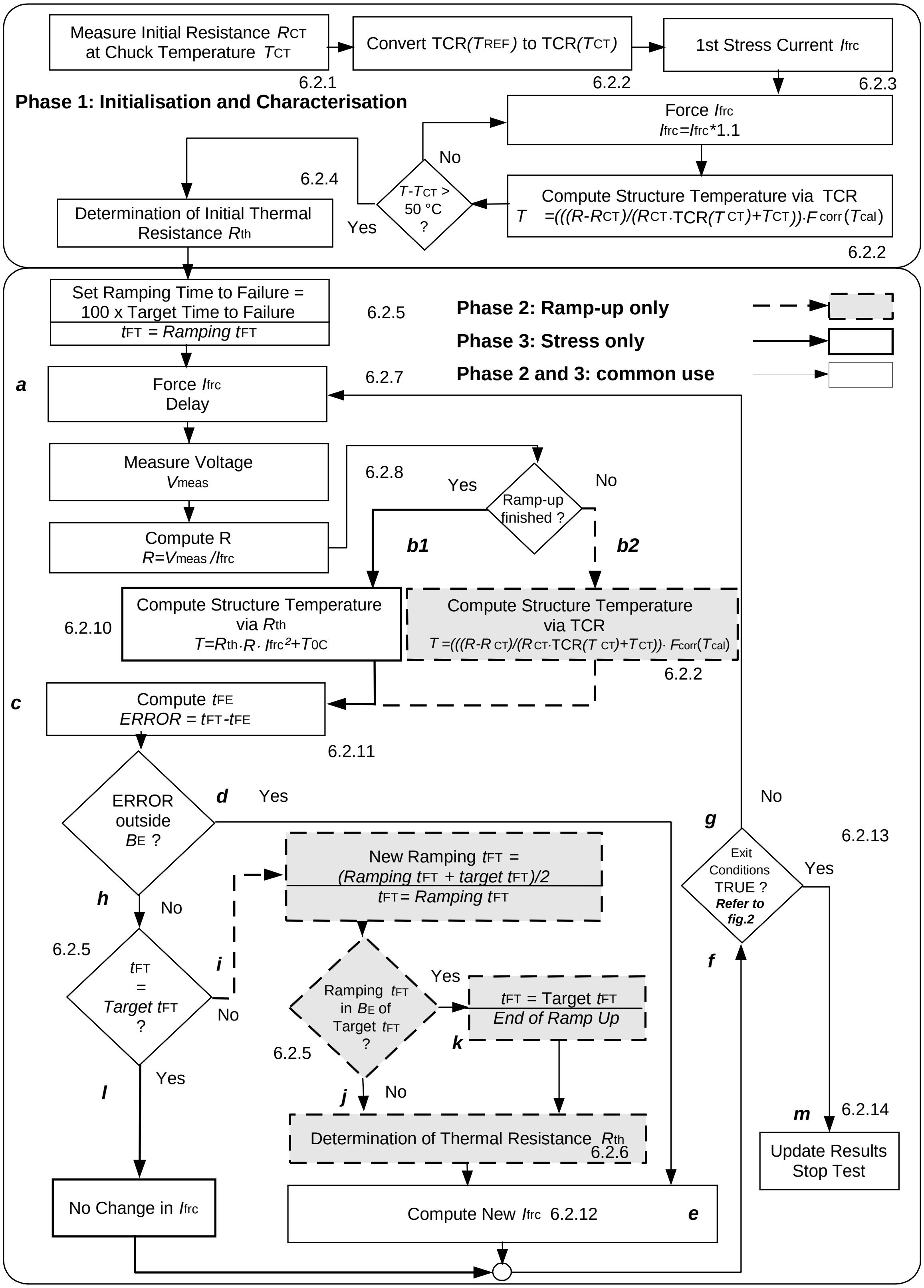

Figure 1 — The SWEAT algorithm (Explanations in section 6.2)

6 The SWEAT algorithm (cont'd)

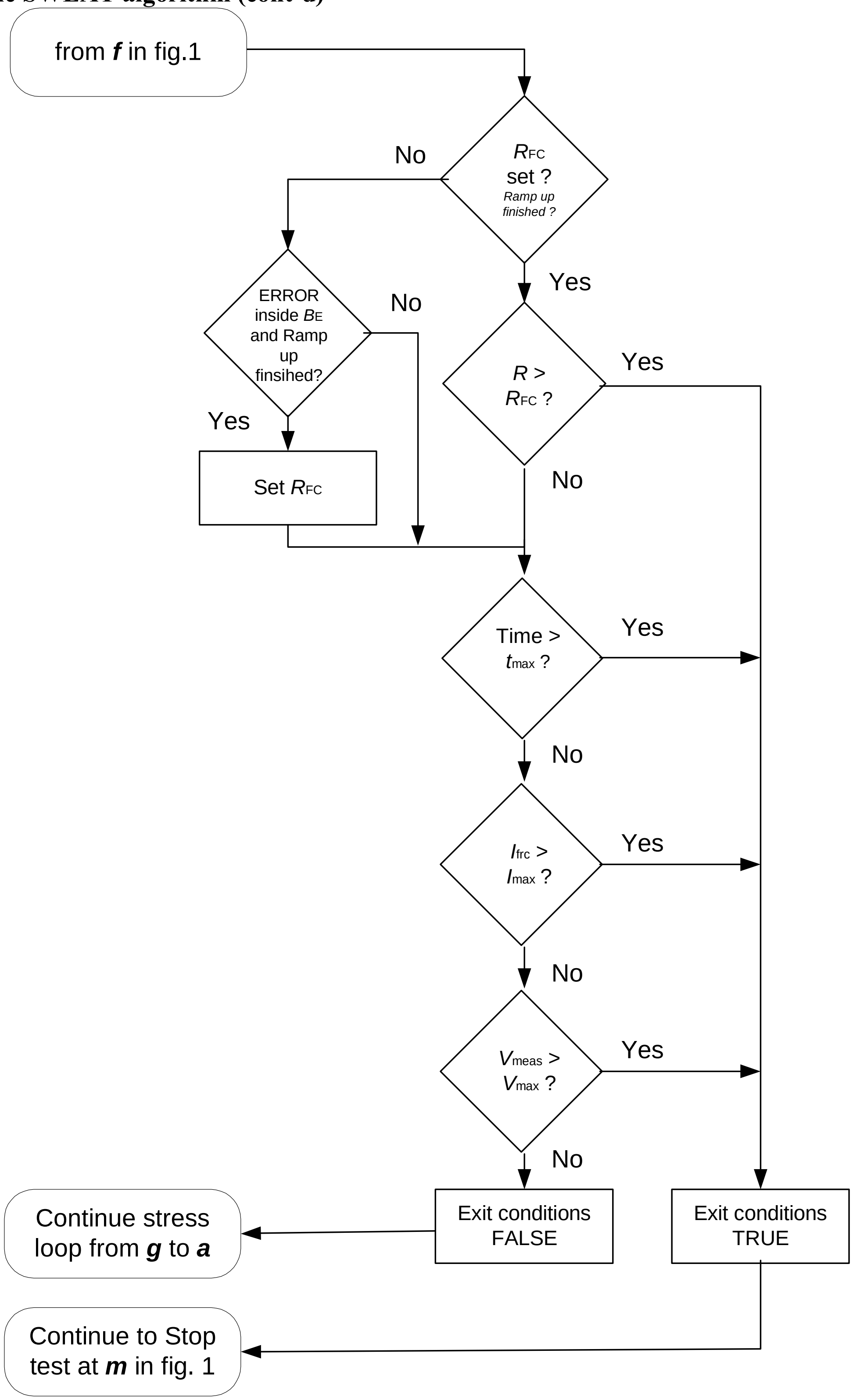

Figure 2—Determining if EXIT conditions are TRUE (Explanations in section 6.2.12)

6.1 Description of SWEAT (cont'd)

6.1.2 Example of SWEAT method

A typical SWEAT test method with the algorithm is illustrated in Figures 3 and 4. The parameters used in the test are listed in table 1.

Table 1 — Typical stress conditions for a straight AlCu-Line

Parameter	Value	Parameter	Value
$F = \Delta R_{last} / R_{last}$	0.10	T_{CT}	30 °C
		TCR(T)	0.0038 1/°C
T_{ref}	30 °C	t_{FT}	60 s
a	1.2 E-8 cm²	B_E	1 s
n	2	A	1.E+11 s A^2/cm^4
		E_a	0.6 eV

The test starts at a high value for the target time to failure. The first stress current is very low. The target value is reduced as long as the estimated time to failure is outside the error band. Reaching the settling point, the target time to failure is switched to the given value, in this example 60 s**.** Figure 3 shows the current and the time to failure during the ramping up phase. As the test progresses, fluctuations of t_{FE} outside of the error band are compensated by the control loop (Figure 4). The small changes in the estimated time to failure that are shown in Figure 4 after entering the error band cannot be seen in Figure 3 because of the scale used. Finally the structure fails at 159.8 s. The stress current decreases continuously due to an EM induced higher resistance of the structure until the failure resistance criterion has been satisfied. During this period, the current density has decreased by 3.5 % and the temperature has increased by 1%.

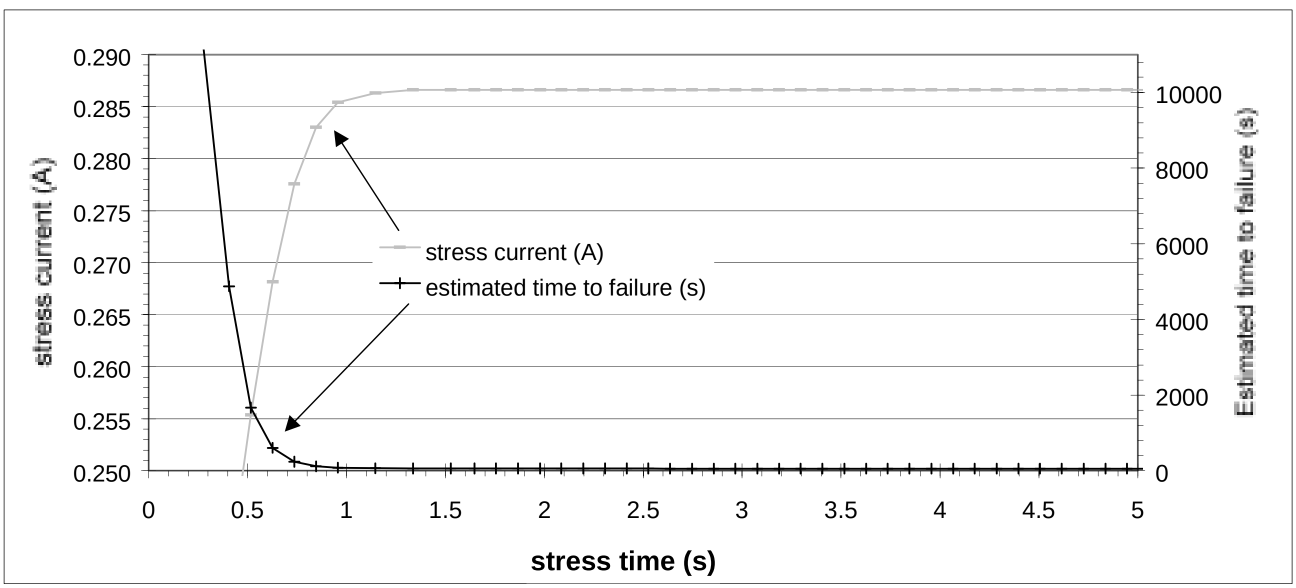

Figure 3 — t_{FE} and stress current versus time during ramp-up

6.1 Description of SWEAT (cont'd)

6.1.2 Example of SWEAT method (cont'd)

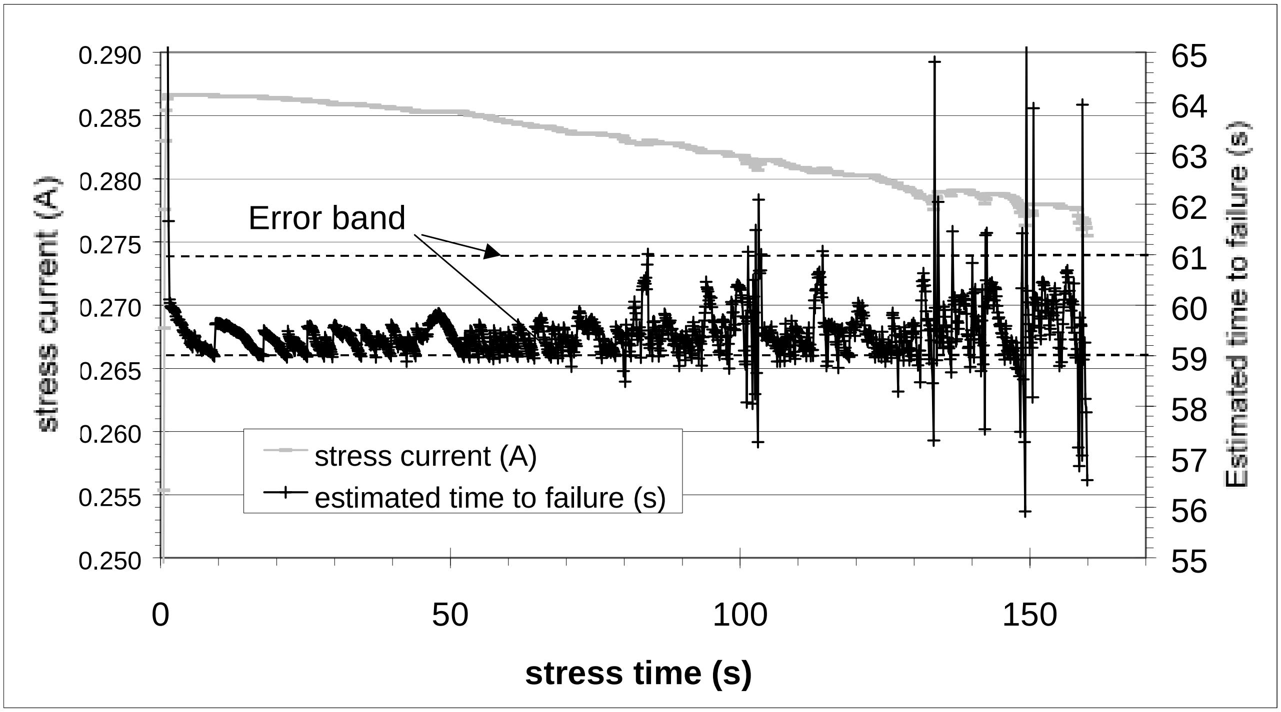

Figure 4 — t_{FE} and stress current versus time for a typical SWEAT test result.

6.2 Explanation of SWEAT flow chart (Figure 1)

The SWEAT flow can be divided in three phases:

Phase 1: Initialization and characterization of the test structure

Phase 2: Ramp-up to stress conditions

Phase 3: Stress with constant conditions

The test steps and the different or common flows for each phase of the test are indicated in Figure 1. A detailed explanation of the test steps follows.

6.2.1 Measure the resistance at chuck temperature, R_{CT}

To measure $R_{CT,}$ at chuck temperature T_{CT}, use a current density that is sufficiently small so that joule heating is negligible. To determine if joule heating is negligible, halve the current and re-measure the resistance. If no significant change in resistance is noted by doing this, the original current used is acceptable. See 7.3 regarding interferences in establishing the initial resistance and temperature.

6.2 Explanation of SWEAT flow chart (Figure 1) (cont'd)

6.2.2 Convert TCR(T_{ref}) to TCR(T_{CT}) and measure temperature

It is assumed that the temperature coefficient of resistance has been measured already for representative parts and a value for TCR(T_{ref}) selected for use in the test. If the chuck temperature is not equal to the reference temperature, the value of the TCR needs to be transformed as shown in equation 5.

$$\mathrm{TCR}(T_{CT}) = \frac{\mathrm{TCR}(T_{ref})}{1 + \mathrm{TCR}(T_{ref}) \cdot (T_{CT} - T_{ref})} \qquad (5)$$

The value for TCR(T_{CT}) is used in the ramp-up stage to calculate the mean temperature T of the test structure from

$$T = T_{cal} \cdot F_{corr}(T_{cal}) \qquad (6)$$

where

$$T_{cal} = \frac{R - R_{CT}}{R_{CT} \cdot \mathrm{TCR}(T_{CT})} + T_{CT} \qquad (7)$$

and R is the resistance of the test structure.

For aluminum test structures, F_{corr}=1.0 for temperatures from room temperature to 420 °C.

For copper test structures, F_{corr}=1.0 for T_{cal} less than 177 °C. For $T_{cal} \geq$ 177 °C (see 4.5 and 7.6)

$$\frac{T}{T_{cal}} = F_{corr}(T_{cal}) = 1.0167 - 8.39751 \cdot 10^{-5} \cdot T_{cal} - 3.74768 \cdot 10^{-8} \cdot T_{cal}{}^{2} \qquad (8)$$

6.2.3 Step increase in forcing current for initial determination of R_{th}

To obtain the initial value for R_{th}, perform the following steps:

a) Use a forcing current through the test structure that is equal to the product of 1.10 and the current used to measure the initial resistance (6.2.1), or some comparable current.

b) After a delay, measure the resistance (R), calculate the temperature (T) using equation 6, calculate the power dissipation ($P = I_{frc}^2 \cdot R$), and store the values for T and P.

c) If T-T_{CT} < 50 °C, multiply the forcing current by 1.10 and return to step b. The increase in temperature of 50 °C here and in d. is a suggested value.

d) If T-$T_{CT} \geq$ 50 °C, go to 6.2.4.

.

6.2 Explanation of SWEAT flow chart (Figure 1) (cont'd)

6.2.4 Determination of initial thermal resistance and T_{0C}

Perform a best straight line fit of the *T* versus *P* data pairs stored (6.2.3) to obtain a linear relation between *T* and *P*, i.e.,

$$T = T_{0C} + R_{th} \cdot P \quad (9)$$

to obtain values for R_{th} and T_{0C}, which are used to calculate the first new forcing current (6.2.12). A correlation coefficient larger than 0.999 is needed to assure that the dependence of temperature on power is sufficiently linear. See 6.2.6.

6.2.5 Ramp up to stress conditions

Select a value for the interim target failure time during ramping, $(t_{FTr})_i$, that is 100 times the target failure time selected for the test, t_{FT}. This is the first interim target fail time, hence i = 1. To prevent any over stress of the test structure because of a steep ramp up of the stress current, begin the ramp up to stress conditions with the value of the largest current used in 6.2.4 (I_{frc1}).

To ramp up to stress conditions, begin the first cycle of the stress loop in Figure 1 (steps a, b2, c, d, and e). Force current I_{frc1}, introduce a delay (6.2.7), measure voltage V_{meas} (6.2.8), compute resistance *R* (6.2.9), calculate temperature *T* (with equation 6) and power dissipation *P* ($I_{frc}^2 \cdot R$), and store *T* and *P*. The new forcing current (to be used in the next cycle) is calculated in step "e" by using equation 14 (6.2.12), which expresses the interim target failure time in terms of the forcing current and is solved for I_{frc} by an iterative technique. Complete the cycle by continuing to steps "f", "g" (6.2.13) and returning to step "a" with the new forcing current

Cycle through the stress loop until the estimated time to failure, t_{FE}, is within the error band B_E of $(t_{FTr})_i$, at step "h" in Figure1. The stress loop is then routed to step "i", where the target failure time during ramping is reduced so that $(t_{FTr})_{i+1} = \frac{1}{2}\{(t_{FTr})_i + t_{FT}\}$. If, for example, t_{FT} is 100 s, then $(t_{FTr})_i$ is 10000 s, 5050 s, 2575 s, ... as i increases starting from $i = 1$. The loop is then routed back to step "a" by way of steps "j", "e", "f" and "g". The initial stress loop ("a" to "g" and back to "a") is used until t_{FE} is again within the error band of t_{FTr} at which point the loop is routed to step "i" where t_{FTr} is decreased again. After each reduction in the interim target failure time, the values for R_{th} and T_{OC} are updated (step "j") using all stored *T*, *P* data where *T* is within 50 °C of the maximum stored temperature. A best straight line fit to the *T* versus *P* data is performed to obtain a new linear relation $T = T_{OC} + R_{th} P$. A correlation coefficient larger than 0.999 is needed to assure that the dependence of temperature on power is sufficiently linear. The updated values of R_{th} and T_{0C} are used to calculate a new forcing current in step "e" (6.2.12).

Continue this process until t_{FTr} is within the error band of t_{FT}. At this time, the stress loop is diverted to step "k" (in Figure 1), after which the target failure time is set permanently to $t_{FT.}$ The ramp-up procedure is now completed. At this point the final values for R_{th} and T_{0C} are determined. They are used henceforth to calculate the temperature of the test structure, using equation 9. The temperature determination is switched from path "b2" (TCR) to path "b1" (R_{th}). The loop is continued to "e" and then to "f" where, as shown in Figure 2, the failure resistance criterion, R_{FC}, is set so that $R_{FC} = R_{last}(1+F)$, where R_{last} is the value of the last resistance measurement of the test structure and *F* is the pre-selected fractional increase in resistance of R_{last} for the test. On returning to "a" in Figure 1, the first cycle of the stress loop for the stress conditions of the test is begun.

6.2 Explanation of SWEAT flow chart (Figure 1) (cont'd)

6.2.6 Determine the thermal resistance R_{th} and T_{0C}

Degradation of the metal line due to electromigration produces uncertain changes[2] in the TCR of the test line. Hence, after the settling period (ramp-up process), the use of TCR (equation 7) to determine the mean temperature of the test line is no longer used. Instead, the linear relationship between power dissipation and the temperature is used, as expressed by equations 3 and 9. This linear dependence of T and P applies only for a limited temperature range (see 7.7). Hence, the values for R_{th} and T_{0C} used in the stress test are calculated from T versus P data within approximately 50 °C of the stress temperature, as described in 6.2.5.

6.2.7 Force the current I_{frc} and delay

This is the first logical block of the feedback control loop. Force the current I_{frc} that was determined either during the last cycle of the ramping up period or was computed in step "e" of Figure 1 (6.2.12). A delay is added in this step of the algorithm to prevent a voltage measurement before the current source has responded to a request for a new current. (Refer to 5.2, 6.1.1 and 7.2)

6.2.8 Measure the voltage

After forcing the programmed current and waiting for the optional delay time, measure the resulting voltage across the test structure.

6.2.9 Compute the resistance

Compute the structure resistance by dividing the measured voltage by the forced current.

6.2.10 Compute the structure temperature

The mean temperature T of the test structure line is calculated from the following equation (refer to 4.6).

$$T = R_{th} \cdot P + T_{0C} \qquad (10)$$

where R_{th} and T_{0C} are the final values that were determined at the end of the ramp-up stage (6.2.5) and where P is the power dissipation ($V_{meas} \cdot I_{frc}$)

6.2.11 Compute estimated time to failure, t_{FE}

The estimated time to failure t_{FE} can be calculated with equation 1 using the current density J_S associated with the forcing current I_{frc} being used, the estimated mean temperature T, and the pre-selected values for A, n, and E_a.

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[2] Schafft, Harry A., Grant, Tammy C., Saxena, A.N., and Kao, Chi-Yi; Electromigration and the Current Density Dependence, pp. 93-99.

6.2 Explanation of SWEAT flow chart (Figure 1) (cont'd)

6.2.12 Compute new force current, I_{frc}

After each determination of the resistance and the temperature of the test structure, the estimated time to failure is calculated via Black's equation (equation 1). This includes steps "a" through "c" in Figure 1. If the difference between the estimated time to failure, t_{FE}, and the target time to failure, t_{FT}, is larger than the error band, B_E, then a new stress current (via steps d and e in Figure1) has to be calculated and used in the next cycle of the stress loop (starting at "a" in Figure 1). The new stress current is based on what value for I_{frc} is needed to achieve the target time to failure, as calculated by Black's equation.

To calculate the new stress current directly from Black's equation (equation 1 in 4.1), t_{FE} needs to be given in terms of its dependence on stress current, namely $t_{FE} = f(I_{frc})$. Users of the method must then use an iterative procedure of their choice to calculate the new value for stress current so that $t_{FE} = t_{FT}$.

The dependence of t_{FE} on stress current comes explicitly from the dependence of t_{FE} on current density, $J = I_{frc}/a$, and implicitly from the dependence of the stress temperature, $T(I_{frc})$, on joule heating. Joule heating of the test line is determined by the relationship between power dissipation, $I_{frc}^2 \cdot R(T)$, in the line and its thermal resistance, R_{th}. This relationship is expressed by

$$T(I_{\text{frc}}) = R_{\text{th}} \cdot I_{\text{frc}}^{\ 2} \cdot R(T) + T_{0\text{C}}\ , \tag{11}$$

where T_{0C} is the calculated temperature from section 6.2.5. But the resistance of the test line, $R(T)$, is effected by temperature, $T(I_{frc})$, through the temperature coefficient of resistance, $\text{TCR}(T_{CT})$, as shown by equation 12.

$$R(T) = R(T_{\text{CT}}) \cdot [1 + (T(I_{\text{frc}}) \cdot [F_{\text{corr,inv}}(T)]^{-1} - T_{\text{CT}}) \cdot \text{TCR}(T_{\text{CT}})] \tag{12}$$

where $F_{corr,,inv}(T)$ is a correction factor to compensate for the non-linearity of TCR for copper metallizations at temperatures higher than 270 °C. Based on section 7.6,

$$\frac{T(I_{\text{frc}})}{T_{\text{cal}}} = F_{\text{corr,inv}}(T) = 1.01535 - 7.21714 \cdot 10^{-5} \cdot T - 6.53459 \cdot 10^{-8} \cdot T^2 \tag{13}$$

This expression for $R(T)$ is inserted into equation 11 and the equation solved for $T(I_{frc})$ and used in Black's equation, where the dependence of fail time is given explicitly as a function of I_{frc}, as shown in equations 14, 15, and 16. The temperature, which is calculated in degrees Celsius, must be expressed in kelvin in equation 14 to determine t_{FT}.

6.2 Explanation of SWEAT flow chart (Figure 1) (cont'd)

6.2.12 Compute new force current, I_{frc} (cont'd)

$$t_{FT} = A \cdot \left(\frac{I_{frc}}{a} \right)^{-n} \cdot e^{\frac{E_a}{k \cdot (T(I_{frc}) + 273.2K)}} \tag{14}$$

where

$$T(I_{frc}) = \frac{R_{th} \cdot I_{frc}{}^2 \cdot R(T_{CT}) \cdot (1 - T_{CT} \cdot TCR(T_{CT})) + T_{0C}}{1 - R_{th} \cdot I_{frc}{}^2 \cdot R(T_{CT}) \cdot [F_{corr,inv}]^{-1} \cdot \mathrm{TCR}(T_{CT})} \tag{15}$$

and where an approximate value for $R(T_{CT})$ is calculated from

$$R(T_{CT}) = \frac{R(T)}{(T \cdot [F_{corr,inv}(T)]^{-1} - T_{CT}) \cdot \mathrm{TCR}(T_{CT}) + 1} \tag{16}$$

by using the last measured value for $R(T)$, the last value for T (calculated from equation 11), the last value for $F_{corr,inv}(T)$, and the value for TCR(T_{CT}) determined before the test. This gives a value for $R(T_{CT})$ that accounts approximately for the effect of any change in the value for TCR(T_{CT}) due to electromigration. F_{corr} corrects the TCR value for copper (refer to 7.6). For aluminum $F_{corr} = 1$.

The remaining step is to solve equation 14 for the new value for I_{frc} by an iterative technique that is left to the programmer to select and use.

6.2.13 Determine if EXIT conditions are TRUE

Use the method described in figure 2 to determine if the exit conditions are true. To determine if exit conditions are true, first determine if the initial settling period has been completed. The initial settling period is completed the first time that t_{FE} is within the error band of the target failure time, t_{FT}. The failure resistance criterion, R_{FC}, is then set by multiplying the measured resistance of the structure by one plus the fractional increase in resistance selected as the failure criterion. The upper bound of the multiplication factor should be 2.0. Typical values are 1.1 to 1.2.

In summary, exit conditions are TRUE if any of the following is true:

1) R_{FC} has been set and the current structure resistance is greater than or equal to R_{FC}. This is the expected exit condition for the test. The structure resistance has increased such that the resistance is greater by a programmer-determined factor than the resistance at the end of the ramp-up stage.

2) Total testing time (t_{max}) has expired.

3) A new force current has been computed which is larger than the current limit (I_{max}) of the power supply.

4) Voltage compliance (V_{max}) of the source has been reached.

6.2 Explanation of SWEAT flow chart (Figure 1) (cont'd)

6.2.14 Update results, stop test

The results to report upon exiting the test are as follows.

Required Results:

- Time to failure (t_F), see 4.12.
  Should the test exit for conditions other than due to electromigration-driven failures, the value t_F should not be used.
- Description of test structure used.
  The width and thickness of the test structure and its termination by a diffusion barrier (e.g., via contact) have a direct influence on the t_F. Therefore, a description of the test structure is necessary.
- The fractional increase in resistance *(F)* used to set R_{FC} see 6.2.5.

Optional Results:

- Resistance at failure (R_F) see 4.13.
- Current density at failure (J_F) see 4.14.
- Temperature at failure (T_F), see 4.15.
- The initial settling time, see 6.2.5.
- The exit condition that caused the test to terminate. see 6.2.13.

7 Interferences

7.1 Temperature gradients

Test results and their interpretation can be impacted by anything that promotes joule-heating non-uniformities along the test line between the voltage taps used to monitor resistance. Local changes in the design features of the test structure, such as changes in linewidth, and other localized changes in their thermal-resistance-to-ambience lead to temperature gradients in the joule-heated test line. These gradients impact the estimate of the mean stress temperature of the test line and can, if sufficiently large, create unrealistic stress conditions and impact the location of the failure site.

7.2 Feedback control time and sampling

For wafer level testing, the thermal response time of narrow-line test structures due to a current change is less than a few microseconds. Hence, the feedback control time is primarily effected by the response of the current source to a requested change in current. A delay is added to make sure that the new current has stabilized before the voltage measurement is made. While modern test equipment often allows for sample times less than 10 ms, shorter times do not give further improvement in the information about the status of the test structure.

7 Interferences (cont'd)

7.3 Control of ambient temperature

It is recommended that a temperature-controlled wafer-chuck or some other means be used to keep constant the ambient temperature of the wafer during these stress tests. The temperature to which the wafer is controlled should normally be no higher than necessary to maintain a stable temperature of the wafer. This temperature might be the same temperature at which normal parametric tests would be conducted.

Keeping the temperature of the wafer constant, can avoid several sources for measurement interference that could lead to errors of interpretation in a given test and in tests conducted at different times. For example: The testing of many structures over a wafer on a chuck with no temperature control can gradually increase the temperature of the chuck and wafer due to the joule heating associated with the tests. At the same time, the ambient temperature of the room could change by as much as several degrees over the period of such tests. Furthermore, the mean and the spread of the ambient temperatures could also differ significantly from one season to the next. The resultant uncertain variabilities in the ambient temperature of the wafer would be reflected in the stress conditions of the tests and, hence, in the failure times recorded.

7.4 Four-wire kelvin test configuration

The structure must have separate contact pads for voltage taps to the test line. Placing two probes on one pad, one to carry current and one to measure voltage, is not an effective Kelvin test configuration

7.5 Initial settling time

Initial settling time is an optionally reported result (see 6.2.14). Some users of the SWEAT method have subtracted the initial settling time from the time at which the structure failed to arrive at the failure time t_F. In general, initial settling time will have a distribution with a much smaller deviation than that for the t_F distribution. To some extent, this is a function of the t_F. The shorter the failure time, the greater the impact of the settling time on results. By reporting initial settling time, users of the SWEAT method can perform a more thorough evaluation of the results.

7.6 Use of TCR(*T*) to estimate high temperatures

The temperature coefficient of resistance is commonly determined from resistance measurements taken at temperatures ranging from room temperature to perhaps as high as 150 °C. It is then used to estimate test line temperatures during a stress test. The method assumes that the resistance is linearly dependent on temperature up to the higher temperatures where an electromigration stress test is conducted.

7 Interferences (cont'd)

7.6 Use of TCR(T) to estimate high temperatures (cont'd)

The assumption of linearity is satisfactorily for testing aluminum alloy metallizations, but it is not for copper. The resistivity of aluminum begins to deviate significantly from a linear dependence at temperatures higher than approximately 420 °C. This is much higher than the temperatures used in electromigration stress tests of aluminum metallizations. For copper, the deviation from a linear dependence becomes noticeable at temperatures higher than approximately 220 °C. At a temperature of 300 °C, the temperature calculated from the TCR*(T)* value is already too high by about 4 °C. Higher temperatures will lead to increasingly larger overestimates of the test line temperature. Highly accelerated electromigration stress tests of copper lines are conducted such that the stress temperature can be higher than 600 °C. At 600 °C, the TCR*(T)*-determined temperature would be over 30 °C too high. Note that when testing copper lines with low-k dielectrics, the stress temperatures used may need to be considerably lower than 600 °C to prevent thermal degradation of the dielectric.

If the resistance of a test line, R(T), depends linearly on temperature, then

$$R(T) = R(T_0) \cdot \left(1 + \mathrm{TCR}(T_0) \cdot (T - T_0)\right) \tag{17}$$

where: $\mathrm{TCR}(T_0) = \Delta R \big/ \Delta T \cdot \dfrac{1}{R(T_0)}$.

The temperature of a line can be calculated from its change in resistance relative to a reference temperature, T_0, by use of the following rearrangement of equation 17.

$$T = \frac{R(T) - R(T_0)}{R(T_0) \cdot \mathrm{TCR}(T_0)} + T_0 \tag{18}$$

Neglecting any dimensional changes (due to thermal expansion) of the test line for the temperatures considered, the dimensional parameters of equation 18 can be canceled. Equation 18 can then be rewritten in terms of changes in resistivity with temperature. Assuming that copper obeys Matthiessen's rule[3], then the resistivity of the copper line can be given by

$$\rho(T) = \rho(T)_{\mathrm{PB}} + \rho_{\mathrm{r}}(c)\,, \tag{19}$$

where $\rho(T)_{\mathrm{PB}}$ is the resistivity of pure, bulk copper and $\rho_{\mathrm{r}}(c)$ is a temperature-independent residual resistivity. Equation 18 can then be expressed as follows

$$T = \frac{\rho(T)_{\mathrm{PB}} - \rho(T_0)_{\mathrm{PB}}}{\left(\Delta\rho \big/ \Delta T\right)_{\mathrm{PB}}} + T_0\,. \tag{20}$$

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[3] Schuster, Constance E., Vangel, Mark G., and Schafft, Harry A., *Improved estimation of the resistivity of pure copper and electrical determination of thin copper film dimensions*, Microelectronics Reliability 41, 2001, pp. 239-252.

7 Interferences (cont'd)

7.6 Use of TCR(T) to estimate high temperatures (cont'd)

In summary, the assumption that the dimensional terms of the resistance cancel in equation 18 and that equation 19 applies, the temperature of a line can be calculated either from the change in resistance or from the change in the resistivity of pure, bulk copper with temperature.

Selected values for the resistivity of pure, bulk copper[3] are listed with increasing temperature in Table 2. The results of a linear regression of resistivity versus temperature (in °C), using the values from Table 2, provide values for a and b in the linear expression for resistivity: $\rho(T)$ = a + b T(°C).

Table 2 — Resistivity of pure, bulk copper as a function of temperature (in kelvin and in degree Celsius), and the results of a linear regression analysis

T (K)	T (°C)	ρ (μΩcm)
300	26.8	1.72324
330	56.8	1.92527
350	76.8	2.06022
370	96.8	2.19549
400	126.8	2.39916
430	156.8	2.60395
450	176.8	2.74119
For 300 K ≤ T ≤ 450 K (27 °C ≤ T ≤ 177 °C): $\rho(T)$= a + b T r^2 = 5N a = 1.5398 b = 0.0067863		

To calculate the temperature, T_{cal}, of the test structure at temperatures beyond where the linear dependence holds, equation 21 was used, which is the same as equation 20 except that the change in resistivity with temperature is represented by the parameter b from Table 2.

$$T_{\text{cal}} = \frac{\rho(T)_{\text{PB}} - \rho(T_0)_{\text{PB}}}{b} + T_0 \qquad (21)$$

In making the calculations of T_{cal}, T_0 was set equal to 176.8 °C and values for the resistivity of pure, bulk copper from reference 3 were used for a selection of temperatures up to a temperature of 676.8 °C (950 K). The results of such calculations are shown in Table 3, where the difference between the calculated temperature and the actual temperature, T_{cal} - T_{real}, increases from zero as the temperature increases beyond 176.8 °C. At an actual temperature of 676.8 °C, the difference is 45.5 °C. Also shown are selected values for the ratio T_{real}/T_{cal} that are used to generate functions T_{corr} and $T_{corr,inv}$.

7 Interferences (cont'd)

7.6 Use of TCR(T) to estimate high temperatures (cont'd)

Table 3 — Temperature deviation associated with resistivity for pure bulk copper

T_{cal} (°C)	ρ(T) (µΩcm)	T_{real} (K)	T_{real} (°C)	T_{cal}-T_{real} (°C)	T_{real} / T_{cal}
176.8	2.7412	450	176.8	0	1
197.1	2.8791	470	196.8	0.3	0.99847793
227.8	3.0871	500	226.8	1	0.99561018
258.7	3.2968	530	256.8	1.9	0.99265559
279.4	3.4375	550	276.8	2.6	0.99069435
305.5	3.6145	575	301.8	3.7	0.98788871
331.7	3.7927	600	326.8	4.9	0.98522762
363.5	4.0084	630	356.8	6.7	0.98156809
384.9	4.1533	650	376.8	8.1	0.97895557
406.4	4.2991	670	396.8	9.6	0.97637795
438.8	4.5194	700	426.8	12	0.97265269
471.6	4.7419	730	456.8	14.8	0.96861747
493.6	4.8914	750	476.8	16.8	0.96596434
515.8	5.042	770	496.8	19	0.96316402
549.4	5.2696	800	526.8	22.6	0.95886422
583.3	5.4995	830	556.8	26.5	0.95456883
606	5.6541	850	576.8	29.2	0.95181518
629	5.8098	870	596.8	32.2	0.94880763
663.7	6.0452	900	626.8	36.9	0.94440259
698.7	6.2832	930	656.8	41.9	0.94003149
722.3	6.4432	950	676.8	45.5	0.93700678

The correction factor $F_{corr}(T_{cal})$ to obtain T (°C) when T_{cal} (°C) is known is given by

$$F_{corr} = \frac{T}{T_{cal}} = f(T_{cal}(°C)) = 1.0167 - 8.39751 \cdot 10^{-5} \cdot T_{cal} - 3.74768 \cdot 10^{-8} \cdot T_{cal}^2 \qquad (22)$$

and the correction factor $F_{corr,inv}(T)$ to obtain T_{cal} when T is known is given by

$$F_{corr,inv} = \frac{T}{T_{cal}} = f(T(°C)) = 1.01535 - 7.21714 \cdot 10^{-5} \cdot T - 6.53459 \cdot 10^{-8} \cdot T^2 \qquad (23)$$

These functions give, respectively, the opportunity to correct (with equation 22) the temperature measured with TCR, i.e., T_{cal}, to its actual value; and to calculate the TCR temperature (from equation 23) and there from to estimate the resistance of the test line at the initial temperature (6.2.12).

It should be noted that the corrected temperature obtained from equation 22 is still only an estimates of a mean stress temperature of the test structures. Because of the high current densities of the stress test, significant temperature gradients will exist at regions where, for example, there are changes in linewidth.

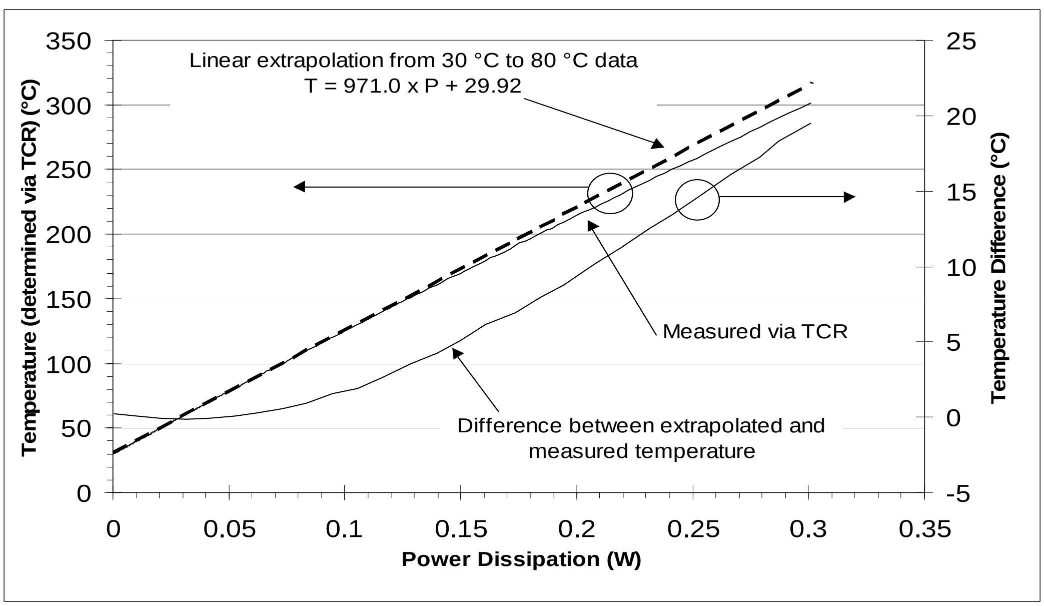
7 Interferences (cont'd)

7.7 Regarding the temperature dependence of the thermal resistance

A plot of the temperature rise of a test line versus the power dissipation in that test line will display a generally linear dependence, where the thermal resistance is the value of the slope of that line. A best straight line fit to the temperature versus power dissipation data may reveal a relatively high correlation coefficient of perhaps as large as 0.999. This may lull the user to believe that if R_{th} and T_{0C} are calculated from data taken at low temperatures (e.g., between 30 °C and 80 °C), these values can be used to estimate the much higher test line temperatures during the stress phase of the test.

A closer examination of such a plot will show a gradual change in the slope of the line for increasing power dissipation. Examples of this behavior are shown in figs 5 and 6 for aluminum and copper test lines, respectively. This gradual change in slope can lead to errors in calculating the stress temperature of a test line from its power dissipation. This will happen if the value of the thermal resistance used was calculated from data where the temperatures are much lower than the temperature of the stress test.

The temperature scale on the right hand side of Figures 5 and 6 represents the difference between the temperature calculated from a linear extrapolation of the *T* versus *P* data for the temperature range 30 °C to 80 °C, and the corrected temperature calculated from the resistance of the test line and TCR(T_{CT}), using equation 6. This is meant to indicate the magnitude of the error in estimating stress temperature when extrapolating from *T* versus *P* data taken at much lower temperatures than the stress temperature. The error is much more serious when stressing copper metallization than it is for aluminum because of the much higher stress temperatures used in the SWEAT test for copper lines.

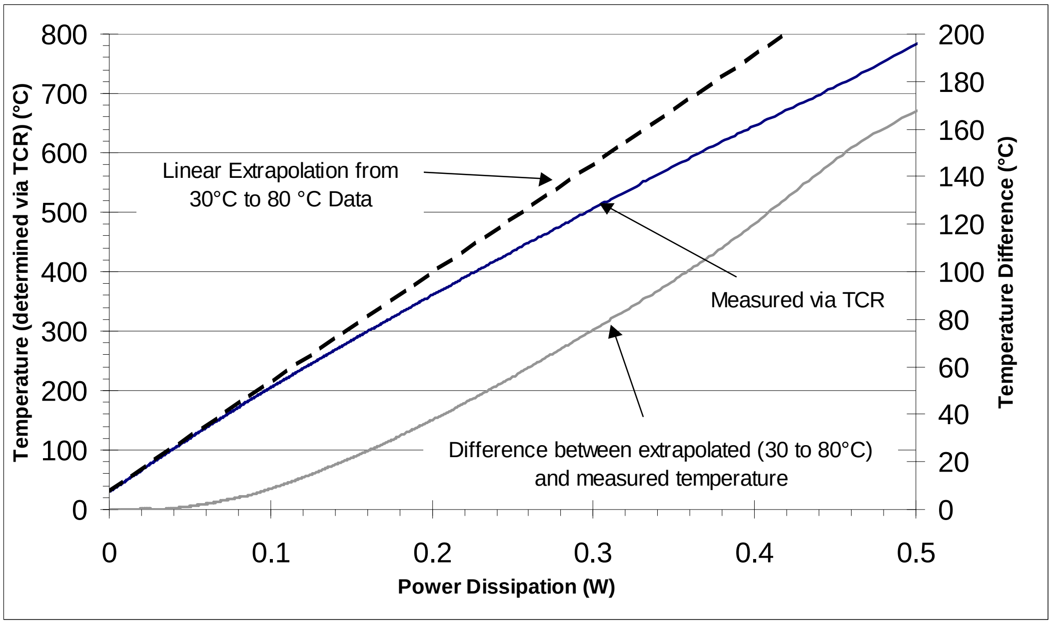


NOTE The correlation coefficient for a best straight-line-fit of the all the *T* vs. *P* data is 0.999.

Figure 5 — *T* vs. *P* for an Al-metallization

7 Interferences (cont'd)

7.7 Regarding the temperature dependence of the thermal resistance (cont'd)



NOTE The correlation coefficient for a best straight-line-fit of the all the *T* vs. *P* data is 0.997.

Figure 6 — *T* vs. *P* for a Cu-metallization

Over a range of approximately 50 °C, the temperature of the test line can be assumed to be a linear function of power dissipation. Hence, to avoid serious errors in estimating stress temperature, the value for the thermal resistance used to calculate the stress temperature of the line during the stress test is obtained from the slope of the *T* versus *P* data in the temperature range of approximately $T_{\text{stress}} - 50\ °C < T_{\text{stress}}$, as is prescribed in the procedure, section 6.2.5.

That the slope of the curves in Figures 5 and 6 decrease slightly with power dissipation is due predominantly to the temperature dependence of the materials in the path of the heat flow from the test line to the wafer chuck. The materials are the silicon of the wafer and the interposing dielectric, which in the two cases above is silicon dioxide. The thermal conductivity of silicon dioxide increases with increasing temperature, while the thermal conductivity of silicon decreases. Because the thermal conductivity of silicon is so much greater than that of silicon dioxide, most of the temperature drop occurs in the silicon dioxide. Hence, it is the temperature dependence of the silicon dioxide that dominates. Because thermal resistance is inversely proportional to the thermal conductivity, we see a gradual decrease in the slope in Figures 5 and 6 as the temperature increases.

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