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Standard Method for Measuring and Using the Temperature Coefficient of Resistance to Determine the Temperature of a Metallization Line

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(From JEDEC BoD Ballot JCB-03-64, formulated under the cognizance of the JC-14.2 Subcommittee on Wafer-Level Reliability.)

1 Scope

This method is intended for determining the temperature coefficient of resistance (at a given temperature) of aluminum- and copper-based thin-film metallizations that are used in microelectronic circuits and devices.

This method is intended for estimating a mean temperature of a metallization line stressed in an accelerated electromigration stress test before any irreversible change in resistivity occurs due to the current-density and temperature stresses imposed.

This method is intended for using a metallization test line as an ambient-temperature sensor. It uses the predetermined values for the temperature coefficient of resistance of the metallization and the resistance of the test line at a reference temperature.

This method is designed for use under conditions where the metallization resistivity is linearly dependent on temperature and where it does not suffer any irreversible changes. For aluminum metallizations, a linear dependence appears to hold until approximately 420 ºC, considerably above anticipated stress temperatures. For copper metallizations, a departure from a linear dependence becomes evident at temperatures as low as 200 °C. A correcting function is used for copper to correct for departures from linearity at these higher temperatures

This method is applicable to metallization test lines with or without vias, and with oxide or low-k dielectrics.

While the method is designed for use with aluminum- and copper-based metallizations, it may also be used with other metals and alloys for conditions that satisfy the linear dependence and stability stipulations in the previous paragraphs.

The metallization structure used in the method may be measured while on a wafer or a part therefrom, or as part of a test chip bonded to a package and electrically accessible via package terminals.

2 Introduction: significance and use

The temperature increase of a test line due to Joule heating can be an important parameter in accelerated stress tests used to characterize the susceptibility of a metallization test line to electromigration failure at a given temperature and current density [l], [2], [3]. A measure of this susceptibility is the median-time-to-failure of test lines in such tests. Accurate knowledge about the metallization temperature during the test is important because the median-time-to-failure is exponentially dependent on the reciprocal of the metallization stress temperature, in kelvin. For example, an error of five degrees in stress temperature introduces a 25% error in the sample estimate for t_{50} at a line temperature of 150 °C and when the activation energy is 0.7 eV)[1].

2 Introduction: significance and use (cont'd)

Electromigration is a metallization failure mechanism that is of great concern, especially for the reliability assessment of very large scale integrated (VLSI) microelectronic devices.

The linear dependence of the resistance of the metallization on temperature permits a test line to be used as a temperature sensor as long as the environmental conditions do not cause irreversible changes in the resistivity of the metallization.

By using the temperature dependence of the resistivity of pure, bulk copper, it is possible to make temperature determinations beyond the linear range for copper. This done by using a correction factor, which is a function of the temperature that is calculated when a linear dependence is nevertheless assumed to exist.

Metals such as aluminum and copper obey Matthiessen's rule [4] to a good approximation. In this case, the resistivity of the metal is the sum of the resistivity of the pure, bulk form of the metal, $\rho(T)_{PB}$, and a temperature-independent residual resistivity, $\rho(c)_r$. This residual component is due to impurities and to other departures from the structural order that contributes to electron scattering. The greater the residual resistivity, the smaller will be the value of the temperature coefficient of resistance, as can be seen in the following equations.

$$TCR(T) = \frac{1}{R} \times \frac{dR}{dT} = \frac{1}{\rho(T)_{PB} + \rho(c)_r} \times \frac{d\rho(T)_{PB}}{dT} = \frac{1}{\rho(T)_{PB}} \times \frac{d\rho(T)_{PB}}{dT} \times \frac{1}{1 + \frac{\rho(c)_r}{\rho(T)_{PB}}}$$

$$\text{or} \qquad TCR(T) = TCR(T)_{PB} \times \frac{1}{1 + \frac{\rho(c)_r}{\rho(T)_{PB}}}.$$

The maximum value for TCR(T) at any given temperature will therefore occur when the residual resistivity is zero. Hence, for example, one can expect that the TCR(T = 30 °C) for aluminum and copper will be no larger than approximately 0.00414 °C^{-1} and 0.00389 °C^{-1}, respectively. (See reference 5 and Annex A.) The magnitude of the residual resistivity, relative to the resistivity of the pure, bulk metal, is obtained from

$$\frac{\rho(c)_r}{\rho(T)_{PB}} = \frac{TCR(T)_{PB}}{TCR(T)} - 1.$$

3 Terms and definitions

3.1 metallization: A thin-film conductive material used to electrically connect microelectronic elements.

3.2 temperature coefficient of resistance: The fractional change in resistance of a test line per unit change in temperature at temperature T,

$$\mathrm{TCR}(T) = \frac{1}{\mathrm{R}(T)}\, x\, \frac{\Delta R}{\Delta T} \quad \left({}^{\circ}\mathrm{C}^{-1}\right), \tag{1}$$

where $R(T)$ is the resistance of the test line at temperature T (see 4.2.3).

NOTE For aluminum-based metallizations, the change in resistance of the test line with temperature is approximately constant from room temperature to about 420 °C (see Annex A). For copper-based metallizations, a change in $\Delta R/\Delta T$ becomes evident at temperatures as low as 230 °C. Hence, if TCR(T) is to be used to calculate the temperature of copper test lines at such higher temperatures, a correction function, F_{corr}, will be required (see Annex A).

3.3 test line: A metallization line of specified dimensions, whose length is defined by the locations 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.

3.4 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. (See 4.4.1, 13.1c, 13.2b, 13.3a.)

4 Summary of method

4.1 Assumptions

The method is based on two assumptions:

4.1.1 Assumption 1

The resistance of the metallization test line is a linear function of the metallization temperature. Hence, the resistance at a temperature T can be given by:

$$R(T) = R(0) + S \times T \ , \tag{2}$$

where S is the slope of the resistance-versus-temperature line and $R(0)$ is the resistance of the test line at an ambient temperature of 0 °C, as illustrated in Figure 1. (See 5.1.) Another assumption will be used to permit measurements of copper test structures at high temperatures where linearity no longer holds. (See Annex A.2.

4.1 Assumptions (cont'd)

4.1.1 Assumption 1 (cont'd)

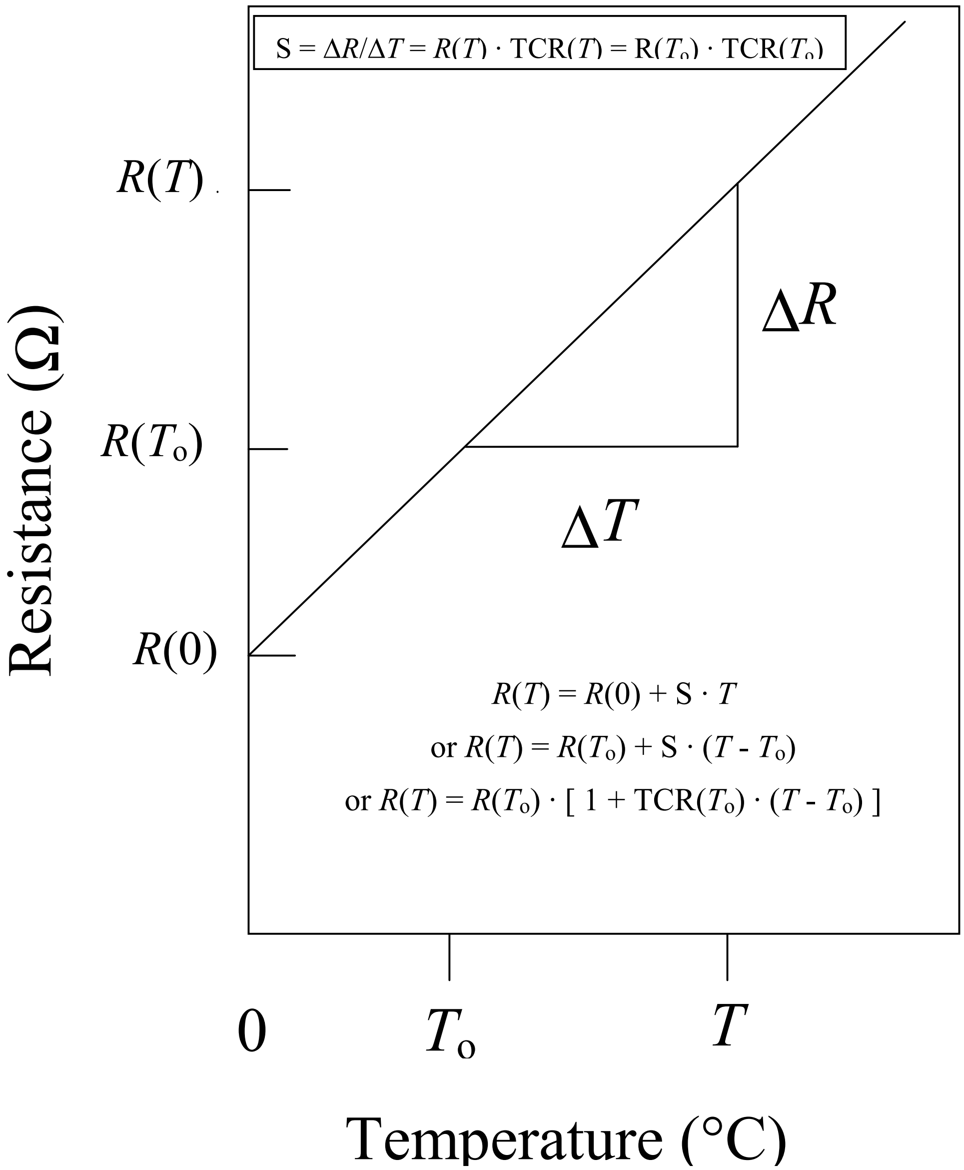

Figure 1 — Illustration of terms used in text on a plot of resistance versus temperature.

4.1 Assumptions (cont'd)

4.1.2 Assumption 2

The resistivity of the metallization does not suffer any irreversible changes when subjected to the temperatures and currents of the test, thereby permitting repeatable resistance measurements at any temperature and current used with the method. (See 5.2.)

4.2 Relations used

The method uses a number of relations:

4.2.1 Resistance of test line

From the definition for TCR(T) (see 3) and assumption 1 (see 4.1.1), the resistance of the test line at temperature T_0 is related to the resistance at another temperature, T, by the temperature coefficient of resistance of the test line for temperature T_0:

$$R(T) = R(T_0) \times \{1 + TCR(T_0) \times (T - T_0)\}. \tag{3}$$

4.2.2 Intercept and slope

Equation 3 can be rewritten in the linear form of equation 2:

$$R(T) = R(T_0) \times (1 - TCR(T_0) \times T_0) + R(T_0) \times TCR(T_0) \times T \tag{4a}$$

where the intercept at $T = 0$ °C is

$$R(0) = R(T_0) \times (1 - TCR(T_0) \times T_0) \tag{4b}$$

and where the slope is

$$S = R(T_0) \times TCR(T_0). \tag{4c}$$

Because the slope is constant (4.1.1) and T_0 is an arbitrary temperature,

$$S = R(T) \times TCR(T) = R(T_0) \times TCR(T_0). \tag{4d}$$

The purpose of equation 4d is to emphasize that the product of the temperature coefficient of resistance and test-line resistance at one temperature, T, is equal to that product at another temperature, T_0.

4.2.3 Temperature coefficient of resistance

Using equation 4c, the temperature coefficient of resistance at temperature T can be expressed in terms of the slope S and the test-line resistance at temperature T:

$$TCR(T) = \frac{S}{R(T)}. \tag{5}$$

Equation 5 demonstrates that the temperature coefficient of resistance is not a constant; it decreases with increasing temperature because metallization resistance increases with temperature while S remains constant. **Therefore, the temperature coefficient of resistance must always be referenced to a specific temperature.**

4.2 Relations used (cont'd)

4.2.4 Converting TCR(T_0) to TCR(T)

The temperature coefficient of resistance at one temperature, T_0, is related to that at another temperature, T, by:

$$TCR(T) = \frac{TCR(T_0)}{1 + TCR(T_0) \times (T - T_0)} . \tag{6}$$

4.3 Summary of procedures

The method consists of procedures to determine:

1) the temperature coefficient of resistance of a metallization at a specified temperature (i.e., 4.3.1),
2) the mean temperature of the test line due to Joule heating (i.e., 4.3.2), and
3) the ambient temperature of the test line, which is inferred from a measurement of the test-line temperature (i.e., 4.3.3).

4.3.1 Procedure to determine TCR(T_{ref})

The temperature coefficient of resistance of the metallization at a pre-selected reference temperature, T_{ref}, is determined as follows:

4.3.1.1 Measure $R(T)$ at several temperatures

Measure the resistance of the test line at four or more ambient temperatures, uniformly distributed over a preselected temperature range (see 4.4.3). The maximum temperature selected shall be less than 180 °C for copper lines. This temperature limit is recommended for aluminum lines. (See 4.4.3, 5.1, 5.4, and 5.5.)

4.3.1.2 Determine statistical fit of a straight line

Determine the best straight-line fit of the resistance versus temperature data, using an unweighted, least-squares fitting procedure [6] to obtain the slope, S, and the intercept of the straight line with the vertical axis at 0 °C. The latter is the **calculated** resistance of the test line at 0 °C, $R(0)$.

4.3.1.3 Calculate $R(T_{ref})$

Calculate the resistance of the test line at a reference temperature, T_{ref}, from the values obtained for S and $R(0)$ by using equation 2:

$$R(T_{ref}) = R(0) + S \times T_{ref} . \tag{7}$$

4.3 Summary of procedures (cont'd)

4.3.1 Procedure to determine TCR(T_{ref}) (cont'd)

4.3.1.4 Calculate TCR(T_{ref})

Calculate the temperature coefficient of resistance from equation 5:

$$TCR(T_{ref}) = \frac{S}{R(T_{ref})}. \tag{8}$$

4.3.2 Procedure to determine T_{mean}

A mean value for the temperature of the test line due to Joule heating, T_{mean} , is calculated from the following equation

$$T_{mean} = F_{corr} \times T_{cal} = F_{corr} \times \left(\frac{R(T_{mean}) - R(T_a)}{R(T_{ref}) \times TCR(T_{ref})} + T_a \right) \tag{9}$$

where:

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

F_{corr} = 1.0167 – 8.39751 10^{-5} T_{cal} – 3.74768 10^{-8} T_{cal}^2 (see Annex A.2) for copper metallizations when $T_{cal} > 200$ C, and

$R(T_a)$ is the measured resistance of the test line at ambient temperature, $T_{a,}$ before the stress current is applied.

4.3.3 Procedure to determine T_a

The ambient temperature, T_a, of the test-line is calculated from the following equation:

$$T_a = F_{corr} \times \left(\frac{R(T_a) - R(T_{ref})}{R(T_{ref}) \times TCR(T_{ref})} + T_{ref} \right) \tag{10}$$

where:

F_{corr} = 1.0 for aluminum metallizations when Ta ≤ 420 °C and for copper metallizations when $T_a \leq 200$ °C, and

F_{corr} = 1.0167 – 8.39751 10^{-5} T_a – 3.74768 10^{-8} T_a^2 (see Annex A.2) for copper metallizations when $T_a > 200$ °C.

4.4 Parameters to be selected

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

4.4.1 Test structure

The design of the test structure that includes the test line shall be selected. (See clause 3, 5.7, and 5.8.)

4.4.2 Stress current

The stress current I_s used to generate Joule heating shall be selected and reported with the results of the measurements (see 9.4 and 13.2e).

4.4.3 Temperature range

The temperature range within which the resistance of the test line is to be measured for calculating the temperature coefficient of resistance shall be selected. The minimum temperature shall be greater than 0 °C and greater than the dew point of the gas ambient (see 5.11). The temperature range shall not be less than 60 °C to avoid degrading the precision of the method. The maximum ambient temperature for copper lines shall be 180 °C. This temperature limit is recommended for aluminum lines.

4.4.4 Temperatures within the range

The four or more temperatures at which the resistance of the test line is to be measured (see 4.3.1.1) for determining the temperature coefficient of resistance shall be selected so that they are approximately uniformly distributed over the range identified in 4.4.3. (See 13.1f.)

4.4.5 Reference temperature

The temperature, T_{ref}, to which the temperature coefficient of resistance is referenced (see 8.6) shall be selected and reported with the results of the measurement. (See 12.2.)

5 Precautions and measurement interferences

5.1 Linear dependence

An unweighted, least-squares fitting procedure is used to obtain the best straight-line fit of the resistance versus temperature data when determining the TCR(T) of a test line. One output of the analysis of the data is the coefficient of simple determination, r^2, (see [6]). This measure is used as an approximate indicator of linearity. The values of r^2 for resistivity data from pure, bulk aluminum and copper are considerably greater than 0.9999 (4N) over the range from room temperature to 180 °C. If an analysis of the experimental resistance-versus-temperature data results in a $r^2 < 0.9998$ (3N8), an examination of the data and of the measurement procedure shall be necessary to determine the cause. See 8.5.2.

5.2 Stability of resistance

The use of the method requires that the resistance of the metallization be stable so that resistance measurements are repeatable for the currents and temperatures to which the metallization will be subjected.

5.2.1 Annealing-induced changes

Metallizations that have not been sufficiently annealed or otherwise stabilized may exhibit significant changes in resistance during the test, with the passage of time, or both. These changes will introduce measurement error. Knowledge about what stabilizing procedure is necessary is based on experience with the metallization in question.

5.2.2 Temperature-induced changes

Metallizations that are exposed to test temperatures at which further annealing or other changes in the resistivity can occur may result in a degradation of the coefficient of simple determination (r^2), an error in the calculated value of the temperature coefficient of resistance, or both. One may check for such changes in resistance after the determination of the temperature coefficient of resistance by repeating the resistance measurement at the lowest temperature used. The repeat resistance value should agree with the original one to within the repeatability of the measurement at that temperature.

5.2.3 Electromigration-induced changes

Metallizations may undergo electromigration-induced changes in resistivity and in the temperature coefficient of resistance if, in the process of making resistance measurements, the lines are also subjected to high current-density and temperature stresses. Measurement errors due to these changes can be reduced by minimizing the duration of these stresses. Estimates of when such errors will become a concern can be obtained from monitoring the resistance of similar test lines under the same stresses

5.2.4 Impact on estimate of joule heating

During an electromigration accelerated stress test [1],[2],[3] the Joule heating can be reliably estimated only at the beginning of the test, before metallization degradation due to electromigration has occurred.

5.3 Test current

When the resistance of the test line at a given ambient temperature is being measured, the use of too high a test current will produce measurable Joule heating and an overestimate of the resistance.

5.4 Wafer-level measurements

When wafer-level measurements at elevated temperatures are being made, the use of the method requires special attention to spatial non-uniformities and to variations of the wafer temperature.

5.4 Wafer-level measurements (cont'd)

5.4.1 Spatial temperature differences of heated stage

Spatial differences of the temperature on the heated stage, if uncorrected for, will cause correspondingly large errors in resistance measurements of test lines at various locations on the wafer. These spatial differences in temperature may be accentuated when the temperature-controlled stage used to heat the wafer is operated near the high end of its temperature range and where heat loss by convection becomes significant.

5.4.2 Wafer heat loss

The difference between the temperature of the top surface of the wafer and of the temperature sensor in the heated stage may increase as the temperature of the stage increases above room ambient temperature. The difference can be caused by heat loss from the wafer by convection, for example. This will underestimate the temperature of the test line at which the resistance of the line is measured. The placement of a probe card stage over the wafer, as when making electrical measurements, can affect heat loss.

5.4.3 Temperature variations of heated stage

Variations of the temperature of the heated stage with time (as caused by thermal nonequilibrium or by power cycling of the stage to maintain a set temperature), if uncorrected for, will contribute to errors in estimating the temperature at which the resistance of the test line is measured.

5.5 Package-level measurements

When making package-level measurements at elevated temperatures, the use of the method requires special attention to spatial non-uniformities and variations of the temperature in the environmental chamber (oven).

5.5.1 Spatial temperature differences in heated chamber

Spatial differences of the temperature in the environmental chamber (oven), if uncorrected for, will cause corresponding errors in resistance measurements of test lines in packages at various locations in the chamber.

5.5.2 Temperature variations in heated chamber

Variations of the temperature within the environmental chamber with time (as may be caused by thermal non-equilibrium or by power cycling to maintain a set temperature), if uncorrected for, will contribute to errors in estimating the temperature at which the resistance of the test line is measured.

5.6 Thermal equilibrium

When measuring the Joule-heating effect of a constant-stress current, it is necessary to make the measurement of the test-line resistance after thermal equilibrium has been attained. Otherwise, the degree of Joule heating will be underestimated.

5.6 Thermal equilibrium (cont'd)

5.6.1 Thermal response of wafer

For measurements on the wafer in good thermal contact with a temperature-controlled stage, the thermal response time is of the order of microseconds. This may be verified by monitoring the voltage trace on an oscilloscope screen after a step change in current has been made to generate measurable Joule heating. The effect of Joule heating will be indicated by an increase in voltage across the test line after the step increase in current.

5.6.2 Thermal response of package

For measurements performed on packaged specimens, it may take several minutes for the test line to be in thermal equilibrium with the environment, depending on the package type. To determine how long to wait before attempting to measure the temperature increase of the test line, determine the thermal response of one of the packages to be stressed. The time to wait before the temperature of the test line is to be measured is dependent on the expected temperature increase due to joule heating (ΔT) and on the desired accuracy of the temperature measurement. For example, if ΔT due to Joule heating needs to be known to within 1 °C, the time to wait is given by the time for the line to reach a fraction, F, of the thermal equilibrium temperature as calculated from (1-F) $\Delta T < 1$ °C. For $\Delta T = 20$ °C, F = 0.95; for $\Delta T = 2$ °C, F = 0.5.}

5.6.3 Automated test equipment

If measurements are made using automated equipment that is programmed not to wait until adequate thermal equilibrium has been attained, errors will be introduced. Such errors were detected in an inter-laboratory experiment (see 11.1e and 11.3.2.3).

5.7 Mean temperature of test line

The temperature calculated from resistance measurements of the test line undergoing joule heating will be equal to the mean of the temperature along the test line only when the test line has a constant width and thickness. Changes in width over only a small percentage of the length of the line will still permit an adequate estimate of the mean temperature along the line. Otherwise, the calculated temperature will be the mean of the ratio of the temperature to the cross-sectional area, divided by the mean of the reciprocal of the cross-sectional area. If the test line includes vias, temperature gradients will develop at these locations due to changes in the current density and in the electrical and thermal conductance in and near the vias.

5.8 Peak temperature of test line

The calculated-mean metallization temperature due to joule heating will differ from the peak temperature of the line unless the test line is sufficiently long, uniform in width and thickness, and unaffected by heat sources and sinks. To determine the degree of this difference will require thermal modeling of the test line.

5.9 Accurate voltage measurements

Relatively small sense currents are used to avoid Joule heating in the measurement of test line resistances, such as in determining the TCR(T) and ambient temperature of a test line. To make sufficiently accurate voltage measurements in these determinations, the following good engineering practices are usually necessary. To avoid errors in the measurement of voltage due to thermal and other emf voltages, the mean of the voltages measured with both current polarities must be used in a resistance determination. Using the mean of several such resistance determinations provide an improved sample estimate of the resistance. The standard deviation of these measurements provides a sample estimate of the repeatability of the measurement. An unusually large standard deviation is a sign that there may be contact or other problems with the procedure being used. (See also Table 1, 11.1d, and 11.3.2.4.)

5.10 Probe cleanliness

In wafer-level testing, the probe contact tips must be kept clean otherwise errors may occur in the voltage measurements. Potential problems with the surface of the probe tips may be minimized by routinely checking for the repeatability of voltage measurements on sequential probe placements on the same test structure. Cleanliness of tungsten probe tips may be maintained by moving the probe tips over a ceramic surface at intervals as may be determined to be appropriate.

5.11 Dew point

If the temperature at which measurements are made is at or below the dew point of the gas environment, surface moisture will lead to shunting current paths and make the test results invalid.

5.12 Temperature sensors

Temperature sensors, such as thermocouples, can lose their calibration if exposed to high temperatures over extended periods of time, as in hot chucks used in wafer lever testing. Periodic calibration checks of such sensors can help to avoid temperature-measurement errors. (See 11.3.3, 11.3.3.1, 11.3.3.2.)

5.13 Concurrent testing

Errors can be introduced if the method is used while other tests are being performed or have been performed that can affect the temperature of the test line being measured.

5.14 Low-k dielectrics

When making measurements with test lines that involve low-k dielectrics, it is advisable to limit stress and ambient temperature appropriately, to avoid degrading the dielectric material. (See Annex A.2.)

5.15 Dependence of TCR(*T*) on test structure processing and design

5.15.1 Processing

The TCR(*T*) is dependent on processing through its effect on the residual resistivity of the metallization. The magnitude of the residual resistivity is affected by physical entities that impact electron scattering in the metal line, for example: impurities, defects, grain boundaries, and interfaces. For this reason, it can be expected that different wafer lots, or even different wafers in the same lot, may have somewhat different values for TCR(*T*). The magnitude of the residual resistivity relative to the resistivity of the pure, bulk metal may be calculated from the value of the TCR(*T*), if Matthiessen's rule holds (see 2.).

5.15.2 Line width

For copper metallizations with line widths less than approximately 1 µm, the TCR(*T*) has been observed to decrease with decreasing line width (and hence grain size) [7]. This means that different copper test structures on a single wafer or even adjacent test structures on a wafer may have different TCR(*T*) values if they have different line widths. To date, no such dependence has been reported for aluminum metallizations.

5.15.3 Vias

Changes in the TCR(*T*) of test lines with vias may be detectable as the length of the line becomes comparable to the dimensions of the via and when the material of the via is different from that of the rest of the test line. For example, aluminum test lines with tungsten vias, can be expected to show the influence of the TCR(*T*) of the tungsten on the measured TCR(*T*) for very short lines. Based on the TCR(27 ºC) of the pure form of these metals, 0.00418 $ºC^{-1}$ (aluminum) and 0.00439 $ºC^{-1}$ (tungsten), the change would be less than approximately 5 % (0.00022 $ºC^{-1}$).

5.15.4 Restrictions

Hence, unless experience indicates otherwise, the TCR(*T*) should only be measured with a test line that has dimensions and has had processing similar to those structures which will use the TCR(*T*) value in determining stress or ambient temperatures.

6 Test apparatus

6.1 Current supply

The current supply for providing the probe or stress current shall be capable of providing a current stable and measurable to within ± 0.2% of the current used to measure the resistance of the test line.

6.2 Voltmeter

The voltmeter to measure the voltage across the voltage taps of the test line shall have a voltage display resolution of 0.1% of the display voltage. (See 11.3.2.4.)

7 Ambient temperature controller

7.1 Wafer-level measurement

The temperature of the temperature-controlled stage used to make wafer-level measurements shall be monitored by a sensor that is in good thermal contact with the stage and has a temperature display resolution of 0.1 °C. (See 5.4 and 5.12.)

7.2 Package-level measurement

The temperature of the chamber interior used for testing packaged test structures shall be monitored by a sensor that has a display resolution of 0.1 °C. (See 5.5 and 5.12.)

8 Procedure for TCR(T_{ref}) measurement

8.1 Adjust ambient temperature

Adjust, as necessary, the ambient temperature of the test line to attain one of the temperatures selected in 4.4.4 at which the resistance of the test line shall be measured.

8.2 Determine ambient temperature

Read the temperature-sensor display and make any appropriate corrections to estimate the ambient temperature of the test line, T_1. (See 5.4, 5.5, 5.12, and 5.13.)

8.3 Measure resistance of test line at temperature T_1

8.3.1 Select current

Select a measurement current I_m for the test line that is not large enough to produce measurable Joule heating in the metallization. (See 5.3.)

NOTE To determine if Joule heating is insignificant, halve the measurement current. If the change in resistance is within the repeatability of the measurement, the original current level is acceptable.

8.3.2 Apply current

Apply measurement current I_m to the test line for a time sufficiently long to permit the measurement of the voltage, V_1, between the voltage taps of the test line. (See 5.4.3, 5.5.2, 5.10, and 5.13.)

8.3.3 Calculate resistance

Calculate the resistance $R_1(T_1) = V_1 / I_m$.

8.3 Measure resistance of test line at temperature T_1 (cont'd)

8.3.4 Reverse current

Reverse the measurement current, measure V_2, and calculate $R_2(T_1) = V_2/I_m$, as indicated in steps 8.3.2 and 8.3.3. (See 5.9.)

8.3.5 Calculate resistance

Calculate the resistance of the test line $R(T_1)$ at ambient temperature T_1 by taking the average of $R_1(T_1)$ and $R_2(T_1)$. (See 5.9.)

8.4 Determine resistance of test line at other temperatures

Follow the procedure in 8.3 for measuring the resistance of the test line at each of the other temperatures selected in 4.4.4. (See 5.2.2.)

8.5 Analyze resistance data

Analyze the data obtained in 8.3 and 8.4 for the test-line resistance as a function of ambient temperature.

8.5.1 Best straight-line fit

Perform a best straight-line fit for the resistance-versus-temperature data using an unweighted, least-squares fitting procedure, where the temperature is the independent variable (see Figure 1 and reference [6]).

8.5.2 Coefficient of simple determination

Calculate the coefficient of simple determination, r^2, (see reference [6]). If $r^2 > 0.9998$, proceed to 8.5.3. Otherwise, return to 8.1 to repeat the procedure with increased control and measurement sensitivity. (See 5.1, 5.2, 5.4, 5.5, 5.9, and 5.12.)

8.5.3 Calculate slope and intercept

Calculate the slope S of the change of-the resistance with temperature and calculate the intercept of the line at 0 °C, $R(0)$.

8.6 Determine TCR(T_{ref})

Calculate the temperature coefficient of resistance at the preselected reference temperature, T_{ref} (see 4.4.5).

8.6.1 Calculate R(T_{ref})

Calculate the resistance of the test line at the reference temperature T_{ref} from the values of S and $R(0)$ obtained in 8.5.3 by using:

$$R\left(T_{ref}\right) = R(0) + S \times T_{ref} \ . \tag{11}$$

8.6.2 Calculate TCR(T_{ref})

The temperature coefficient of resistance at reference temperature T_{ref} is calculated from:

$$TCR\left(T_{ref}\right) = \frac{S}{R\left(T_{ref}\right)} . \tag{12}$$

9 Procedure for measuring test-line temperature due to Joule heating

9.1 Determine ambient temperature of test line

Read the temperature-sensor display and make any appropriate corrections to estimate the ambient temperature of the test line, T_a. (See 5.2.5, 5.4, 5.5, 5.12, and 5.13.)

9.2 Measure resistance of test line at ambient temperature

Measure the resistance of the test line at ambient temperature T_a, $R(T_a)$.

9.2.1 Apply measuring current

Apply dc measuring current I_m (8.3.1) to the test line for a time sufficiently long to permit the measurement of the voltage, $V(T_a)$, between the voltage taps of the test line. (See 5.4.3, 5.5.2, and 5.10.)

9.2.2 Calculate resistance

Calculate the resistance of the test line at the ambient temperature $R(T_a) = V(T_a)/I_m$. (See 5.9.)

9.3 Calculate resistance of test line at reference temperature

Calculate the resistance of the test line at the reference temperature by using the following relation:

$$R(T_{ref}) = \frac{R(T_a)}{1 + TCR(T_{ref}) \times (T_a - T_{ref})}, \tag{12}$$

where values for TCR(T_{ref}) and T_{ref} are obtained from 8.6.2 and 4.4.5, respectively.

9.4 Measure resistance of test line during Joule heating

Measure the resistance of the test line, $R(T_{mean})$, during the application of the stress current, I_s, selected in 4.4.2. (See 5.9.)

9.4.1 Apply stress current

Apply stress current, I_s, to the test line and wait until thermal equilibrium has occurred before measuring the voltage, $V(T_{mean})$, between the voltage taps of the test line. (See 5.4, 5.5, 5.6, 5.10, and 13.2f.)

9.4.2 Calculate resistance

Calculate the resistance of the test line $R(T_{mean}) = V(T_{mean})/I_s$.

9.5 Calculate mean temperature of the test line

Calculate the mean temperature, T_{mean}, due to the Joule heating resulting from the stress current with the following formula (see 5.7 and 5.8 regarding the nature of the mean calculated):

$$T_{mean} = F_{corr} \times T_{cal} = F_{corr} \times \left(\frac{R(T_{mean}) - R(T_a)}{R(T_{ref}) \times TCR(T_{ref})} + T_a \right) \tag{14}$$

where:

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

F_{corr} = $1.0167 - 8.39751\ 10^{-5}\ T_{cal} - 3.74768\ 10^{-8}\ T_{cal}^2$ (see Annex A.2) for copper metallizations when $T_{cal} > 200$ C,

and where TCR(T_{ref}) is obtained from 8.6.2.

10 Procedure for measuring ambient temperature with test line

10.1 Apply measurement current

Apply measurement current I_m (8.3.1) to the test line for a time long enough to permit the measurement of the voltage, V_1, between the voltage taps of the test line. (See 5.2.5, 5.4, 5.5, and 5.10.)

10.2 Calculate resistance of test line

Calculate resistance $R_1(T) = V_1/I_m$.

10.3 Reverse measurement current and calculate resistance of test line

Reverse measurement current, measure voltage V_2 between the voltage taps of the test line, and calculate $R_2(T) = V_2/I_m$. (See 5.9.)

10.4 Calculate resistance mean of test line

Calculate the resistance of the test line $R(T)$ by taking the mean of $R_1(T)$ and $R_2(T)$. (See 5.9.)

10.5 Calculate ambient temperature of test line

Calculate the temperature of the test line from the following relation:

$$T_{cal} = F_{corr} \times \left(\frac{R(T_a) - R(T_{ref})}{R(T_{ref}) \times TCR(T_{ref})} + T_{ref} \right) \tag{15}$$

where:

F_{corr} = 1.0 for aluminum metallizations when $T_a < 420$ °C and for copper metallizations when $T_a \leq 200$ °C,

F_{corr} = $1.0167 - 8.39751\ 10^{-5}\ T_a - 3.74768\ 10^{-8}\ T_a^2$ (see Annex A.2) for copper metallizations when $T_a > 200$ C.

and $R(T)$, $R(T_{ref})$, and $TCR(T_{ref})$ are obtained from 10.4, 8.6.1, and 8.6.2, respectively.

NOTE Here the test line is used as a thermometer to determine the ambient temperature. In 9.1, a temperature sensor display is used to estimate the ambient temperature of the test line.

11 Measurement of bias and precision

Five laboratories and a reference laboratory took part in an inter-laboratory experiment to determine sample estimates of both the within-laboratory repeatability of the reference laboratory and the between-laboratory precision (reproducibility) and bias for the method [8]. The following parameters for Al 1%Si metal lines were determined with wafer-level measurements, using a temperature-controlled wafer stage: 1) TCR(0), the temperature coefficient of resistance at the reference temperature of 0 °C, 2) $\Delta R/\Delta T$, the slope of the resistance-versus-temperature line, 3) $R(0)$, the resistance of the test line at the reference temperature, and 4) $\Delta T = T - T_a$, the temperature increase of the test line due to Joule heating. The results are summarized in Table 1.

Table 1 — Summary of inter-laboratory experiment to determine measurement precision and bias. Measures of precision are one standard deviation sample estimates.

	TCR(0)	**ΔR / ΔT**	**R(0)**	**ΔT ~8 ºC**
Inter-Laboratory Reproducibility	2.5 %	2.1 %	0.6 %	0.14 ºC
Within-Laboratory Repeatability	0.21 %	0.13 %	0.09 %	0.03 ºC
Bias	Nil	Nil	Nil	Nil

11.1 Summary

a) One standard deviation sample estimates for the inter-laboratory reproducibility for measuring TCR(0), $\Delta R/\Delta T$, and $R(0)$ were 2.5%, 2.1%, and 0.6%, respectively. The sample estimates determined for the within-laboratory repeatability for these quantities were 0.21%, 0.13%, and 0.09 %, respectively.

b) One standard deviation sample estimate for the inter-laboratory reproducibility for Joule heating measurements was 0.14 °C, for a mean temperature increase of approximately 8 °C. The sample estimate for the within-laboratory repeatability was 0.03 °C.

c) There was no indication of a significant bias between the measurements of the reference laboratory and those of the participating laboratories for any of the parameters.

d) An important source for variability in these measurements was the mix of equipments used by the participating laboratories, where the meter resolution was often less than that used by the reference laboratory. The within-laboratory repeatability of the measurements of a given parameter was, on the average, a tenth as large as the reproducibility of the between-laboratory measurements.

e) Other sources for variability were related to measurements affected by temperature. One source was the making of measurements before thermal equilibrium had been established. Another source was related to differences in the calibration of the systems used to estimate the temperature of the wafer during the measurements.

11.2 Within-laboratory repeatability

a) The reference laboratory made four sets of measurements over three days to obtain four determinations of TCR(0), $\Delta R/\Delta T$, $R(0)$, and Joule heating. These measurements were made of one test structure on one of the three wafers used in the inter-laboratory experiment.

b) To calculate each of the four sets of values for TCR(0), $\Delta R/\Delta T$, and $R(0)$, resistance measurements were made at four temperatures (at about 22 °C, 65 °C, 105 °C, and 150 °C). At each temperature, five resistance measurements were made and the mean taken as the resistance of the test line at that temperature.

c) The means of the four determinations of TCR(0), $\Delta R/\Delta T$, and $R(0)$ were: 0.003592 $°C^{-1}$, 0.1055 Ω/°C, and 29.376 Ω, respectively. The standard deviations, as percents of these means, were 0.21 %, 0.13 %, and 0.09 %, respectively, and were used as measures for the sample estimate for the repeatability of these determinations.

d) The measure used for the sample estimate of the repeatability of Joule heating measurements is the standard deviation of the temperature increases measured at four times over the three days in which the measurements were conducted.

e) Joule heating was produced by a stress current of 40 mA, that was used at two ambient temperatures. The mean values for the calculations of Joule heating at approximately 22 ºC and 65 °C were, respectively, 9.70 ºC and 10.98 °C. The standard deviation was 0.03 °C for both cases.

11.3 Between-laboratory precision and bias

11.3.1 Laboratory instructions

Each participating laboratory was asked to make prescribed measurements on a specific test structure that had been measured by the reference laboratory. The laboratory was instructed: 1) to make resistance measurements at the nominal temperatures of 22 °C, 65 °C, 105 °C, and 150 °C; 2) to use the measurement and stress currents specified; 3) to use 0 °C as the reference temperature; and 4) to describe the equipment used in the measurements. Test structures on three wafers were used in the experiment.

11.3.2 Reproducibility results

The sample estimate of the inter-laboratory reproducibility of the method to measure a given parameter was determined from the standard deviation of the percent differences between the value measured by the reference laboratory and that reported by a participating laboratory.

11.3.2.1 Of temperature coefficient of resistance

The sample estimate of the reproducibility of TCR(0) measurements from five laboratories was 2.5 %. The TCR(0) values, as measured by the reference laboratory, ranged from 0.003362 $°C^{-1}$ to 0.003592 $°C^{-1}$ and had a mean of 0.003529 $°C^{-1}$.

11.3.2 Reproducibility results (cont'd)

11.3.2.2 Of intercept and slope

The one standard deviation sample estimates for the reproducibility of $R(0)$ and $\Delta R/\Delta T$ measurements were 0.56 % and 2.12 %, respectively. The values for $R(0)$ and $\Delta R/\Delta T$ ranged, respectively, from 17.665 Ω to 29.376 Ω and from 0.06287 Ω/ºC to 0.1055 Ω/ºC.

11.3.2.3 Of Joule heating

The sample estimate for the reproducibility of Joule heating measurements (at nominally 22 °C and 65 °C) from three laboratories is 0.14 °C. The mean temperature increases at the two temperatures were: 7.7 °C and 8.7 °C, respectively. The temperature dependence of the Joule heating is predominantly due to the increase in metal resistivity with increasing temperature. A fourth participating laboratory used an automated control and measurement system that did not permit thermal equilibrium to be established before making measurements. This led to temperature differences that were almost ten times that obtained by the other three laboratories in the experiment.

11.3.2.4 Source of variance

An important source for the magnitude of the variances noted for the between-laboratory measurements is the mix of equipment used where the meter resolution was often much less than that of the reference laboratory. When the reference laboratory used a meter with a resolution of 10 µV, instead of one with 0.1 µV, the variance was comparable to that of the between-laboratory measurements of TCR(0), $R(0)$, and $\Delta R/\Delta T$.

11.3.3 Inter-laboratory calibration of temperature sensors

Subsequent to the measurements of 11.3.1, each participating laboratory was sent a portable, battery-powered, surface-temperature measuring system to assess the differences in the temperature calibrations of the wafer stages used in the experiment. The participating laboratories were asked to compare the readings of this system with the readouts of their system over the temperature range used in the experiment. The system had been used by the reference laboratory to measure the temperature of its wafer stage. It was later compared to a calibrated system, having a one-standard-deviation uncertainty in the correction of less than 0.2 °C.

11.3.3.1 Results

At room temperature, all but one of the participating laboratories registered a temperature that was low by no more than 1 °C. The other laboratory read a temperature that was too high by more than 2 °C. At the highest temperatures (~150 °C), the laboratories read temperatures that were too low by 0.7 °C to 6.3 °C.

11.3.3 Inter-laboratory calibration of temperature sensors (cont'd)

11.3.3.2 Impact on reproducibility

The impact of such temperature measurement differences on determinations of TCR(0), $\Delta R/\Delta T$, and $R(0)$ was simulated, using the data set from one test structure measured by the reference laboratory. Data sets were generated for each participating laboratory by using the same resistance values but ascribing them to different temperatures, according to the differences in their temperature calibrations. These data sets were used to determine values for TCR(0), $\Delta R/\Delta T$, and $R(0)$ that were ascribed to the participating laboratories. Analysis of these data showed that the calibration differences of 11.3.3.1 led to simulated reproducibilities that were approximately half the experimentally determined sample estimates for reproducibility where both temperature and electrical measurement variances are combined.

11.3.4 Measurement bias

Measurement bias between the measurements of the reference laboratory and those of the participating laboratories would be indicated if the mean of the difference values is larger than the estimated standard error of the mean (standard deviation of the difference values divided by the square root of the sample size). No indication of bias was found for the measurements of $\Delta R/\Delta T$ and TCR(0). For the other two parameters, there were indications of small bias of less than 0.3% for $R(0)$ and less than 0.1 °C for Joule heating.

12 Required reporting

Report the following information relevant to determining the temperature coefficient of resistance.

12.1 TCR(T_{ref})

Temperature coefficient of resistance calculated, TCR(T_{ref}) (from 8.6.2), and

12.2 T_{ref}

Reference temperature, T_{ref} (from 4.4.5).

13 **Additional, optional information to report** (Not Required)

13.1 Results of TCR(T) measurements

When reporting the results of temperature coefficient of resistance measurements, the following information can be helpful in describing the measurements and in evaluating the results:

a) Identification of operator(s) of test,

b) Equipment used (see 6 and 7),

c) Dimensions of test line used in test, including those of any vias involved (see 3 and 4.4.1),

d) Nominal metallization alloy of the test line,

e) Measurement current, I_m (from 8.3.1) and current density,

f) Temperatures selected in 4.4.4,

g) Coefficient of simple determination (from 8.5.2), and

h) Calculated resistance of test line at reference temperature, $R(T_{ref})$ (from 8.6.1).

13.2 Results of Joule heating measurements

When reporting the results of measurements to determine the mean temperature increase due to Joule heating, the following information can be helpful in describing these measurements and in evaluating the results:

a) Level of measurement: wafer or package,

b) Dimensions of the test line, including those of any vias involved (see 3 and 4.4.1),

c) Thickness and identification of any underlying and overlying layers and structures that would significantly impact Joule heating,

d) Ambient temperature T_a (from 9.1),

e) Stress current, I_s, (from 4.4.2) and current density,

f) Elapsed time after the stress current was applied that the voltage of the test structure was measured (from 9.4.1) (see 5.6),

g) Values for the temperature coefficient of resistance, TCR(T_{ref}), and the reference temperature, T_{ref}, used in the calculations (from 8.6.2 and 4.4.5), and

h) Calculated temperature increase of the test line due to Joule heating (from 9.5).

13.3 Results of test-line temperature measurements

When reporting the results of measurements where the test line is used to determine the ambient temperature, the following information can be helpful in describing these measurements and in evaluating the results:

a) Dimensions of the test line, including of those of any vias involved (see 3 and 4.4.1),

b) Measurement current, I_m (from 8.3.1) and current density,

c) Values for the temperature coefficient of resistance, TCR(T_{ref}), and the reference temperature, T_{ref} used in the calculations (from 8.6.2 and 4.4.5), and

d) Calculated temperature of the test line (from 10.5).

14 References

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Annex A Use of TCR(*T*) in the nonlinear regime to estimate high temperatures

A.1 For aluminum

The normal use of the TCR method to determine test line temperature requires that the resistance be linearly dependent on temperature up to the higher temperatures where an electromigration stress test is conducted. This assumption of linearity appears to be satisfactory for testing aluminum alloy metallizations for all anticipated stress temperatures. An examination of the recommended values for pure, bulk aluminum [9] shows that a significant deviation from linearity appears to begin only at temperatures higher than approximately 420 °C. This is much higher than the temperature used in electromigration stress tests of aluminum metallizations.

The recommended values for the resistivity of pure, bulk aluminum (corrected for thermal expansion), ρ_{rec}, that were provided in the range of interest are listed below in Table A.1. Linear regressions of the data from 19.8 °C to 126.8 °C and from 19.8 °C to 226.8 °C provided the following results, respectively: $r^2 = 0.999982$ (4N82), $\rho(T) = 2.4225 + 0.011462\ T$; and $r^2 = 0.9999952$ (5N52), $\rho(T) = 2.4227 + 0.011454\ T$. Calculated values for the resistivity are also listed in Table A.1, where the following linear expression was used: $\rho_{cal}(T) = 2.4225 + 0.01146\ T$. The differences between the recommended and the calculated values for resistivity are also listed in Table A.1 to show how well the linear expression is able to predict the resistivity at a given temperature. The difference values are all small for temperatures up to 426.8 °C, *except* for the difference value at 326.8 °C. At that temperature, the recommended value is significantly smaller than the calculated value, and the absolute difference is almost six times the next largest value. This puts into question the value recommended for the resistivity at 326.8 °C. It is clear, however, that the recommended values for resistivity beyond 426.8 °C begin a marked departure from linearity.

Table A.1 — Resistivity data for pure, bulk aluminum as a function of temperature: recommended, ρ_{rec} [9], calculated, ρ_{cal}, and the difference, $\rho_{rec} - \rho_{cal}$.

T(°C)	*T*(K)	ρ_{rec} (Ω cm 10-6)	ρ_{cal} (Ω cm 10-6)	$\rho_{rec} - \rho_{cal}$ (Ω cm 10-6)
- 0.2	273	2.417	2.420	-0.003
19.8	293	2.650	2.649	0.001
26.8	300	2.733	2.730	0.003
126.8	400	3.875	3.876	-0.001
226.8	500	5.020	5.022	-0.002
326.8	600	6.122	6.168	-0.046
426.8	700	7.322	7.314	-0.008
526.8	800	8.614	8.460	0.154
626.8	900	10.005	9.606	0.399

Annex A Use of TCR(*T*) in the nonlinear regime to estimate high temperatures (cont'd)

A.2 For copper

For copper, the deviation from a linear dependence becomes noticeable at temperatures as low as approximately 200 °C. At a temperature of 300 °C, the temperature calculated from the TCR*(T)* value is already too high by almost 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 even 600 °C. At such a high temperature, the TCR*(T)*-determined mean temperature of a test line 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 from 4.2.1

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

where: $TCR(T_0) = \frac{\Delta R}{\Delta T} \times \frac{1}{R(T_0)}$.

From equation 4d in 4.2.2, the calculated mean temperature of the test line, T_{cal}, from the change in resistance with temperature when the assumption of linearity holds is given by

$$T_{cal} = \frac{R(T) - R(T_a)}{R(T_{ref}) \cdot TCR(T_{ref})} + T_a = \frac{R(T) - R(T_a)}{\Delta R / \Delta T} + T_a \tag{18}$$

Neglecting any dimensional changes (due to thermal expansion) of the test line for the temperatures considered, the dimensional parameters in 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 [10], then the resistivity of the copper line can be given by

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

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

$$T_{cal} = \frac{\rho(T)_{PB} - \rho(T_a)_{PB}}{\left(\Delta\rho / \Delta T\right)_{PB}} + T_a . \tag{20}$$

Equations 18 and 20 show that the estimated mean temperature of a line can be calculated either from the change in resistance of the line or from the change in the resistivity of pure, bulk copper with temperature.

Selected best-fit values for the recommended values of the resistivity of pure, bulk copper [10] taken from the literature [11] are listed with increasing temperature in Table A.2. The results of a linear regression of resistivity versus temperature (in °C), using the values from Table A.2, provide values for parameters a and b in the linear expression for resistivity: $\rho(T) = a + b\,T$ (°C). Parameter b is the slope of the resistivity versus temperature line.

Annex A Use of TCR(*T*) in the nonlinear regime to estimate high temperatures (cont'd)

A.2 For copper (cont'd)

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

T **(K)**	***T*** **(°C)**	ρ **(x10^{-6}Ωcm)**
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 (0.999990) a = 1.5398 b = 0.0067863		

The temperature, T_{cal}, which would be calculated at some actual temperature beyond the linear range is given below by equation 21, where parameter b (from Table A.2) replaces $[\Delta\rho/\Delta T]_{PB}$ in equation 20.

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

In making the calculations of T_{cal}, T_0 was set equal to 176.8 °C and best-fit values for the resistivity of pure, bulk copper from reference 10 were used for a selection of temperatures up to 676.8 °C (950 K). The results are shown in Table A.3, where the difference between the calculated temperature and the actual temperature, T_{cal} - T, 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/T_{cal} that are used to develop the correction function F_{corr} (equation 22).

Annex A Use of TCR(*T*) in the nonlinear regime to estimate high temperatures (cont'd)

Table A.3 — Tabulation of values for T/T_{cal} from which equation 22 is developed, where T_{cal} is calculated from equation 21 for temperatures where the resistivity of pure, bulk copper deviates increasingly from being linearly dependent on temperature.

T_{cal} (°C)	$\rho(T)$ (µ·Ωcm) (Ref. 10)	T (K)	T (°C)	$T_{cal} - T$ (°C)	T/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 function $F_{corr}(T_{cal})$ to obtain the estimated mean temperature of a test line, T_{mean} (°C), for a given calculated temperature, T_{cal} (°C), (calculated from equation 21) is given by

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

This correction function is used in equations 14 and 15 (9.5 and 10.5, respectively) to correct the calculated temperature, T_{cal}, when it is beyond the linear regime (when $T_{cal} > 200$ °C).

NOTE The corrected temperature obtained with equation 14 (where significant Joule heating may be present) is still only an estimate of the mean stress temperature of the test line. At the high current densities of the stress test, significant temperature gradients will exist at regions where, for example, there are vias and changes in linewidth.

Annex B (informative) Differences between JESD33B and JESD33-A

This listing briefly describes, by clause/subclause, most of the changes and additions that have been made in this standard, JESD33B, compared to its predecessor, JESD33-A (October 1995). If the change to a concept involves any words added or deleted (excluding deletion of accidentally repeated words), it is included. Some punctuation changes are not included.

1 Scope

- First paragraph changed to include copper-based thin-film metallizations.
- Fourth paragraph changed to permit use of the method at temperatures beyond where the resistance is linearly dependent on temperature.
- After the 4th paragraph, a new paragraph is added to state that the method is applicable to test lines with vias and with low-k dielectrics.

2 Introduction: Significance and use

- First two paragraphs are combined with some changes in wording.
- The last paragraph is expanded to show that the temperature coefficient of resistance is a function of the residual resistivity of the metallization and that it is a maximum when the residual resistivity is zero.

3 Terms and definitions

- The wording in all definitions has been modified, in part, to be consistent with definitions in other JEDEC standards.

4.1.1 Assumption 1 (Summary of method)

- Another assumption, necessary for copper metallizations, and Annex A.2 are mentioned.
- Figure 1 has been redrawn.

4.2 Relations used

- Subclauses have been given titles. Some minor word changes have been made in the text.
- Symbols T′ and T have been changed to T and T_0, respectively.

4.3 Summary of procedures

- Title has been changed by adding “Summary of” to the title.
- The text directly below the title has been changed to a listing of the procedures.
- All subclauses have been given titles.
- In subclause 4.3.1.1, a restriction on the maximum temperature for copper metallizations has been added. This restriction is recommended for aluminum metallizations.
- In 4.3.2, the mean value for the temperature of the test line due to Joule heating is calculated instead of the temperature increase from the ambient temperature due to Joule heating.
- In subclause 4.3.1.2, the temperature is now identified as the *ambient* temperature.

Annex B (informative) Differences between JESD33B and JESD33-A (cont'd)

- In both 4.3.1.1 and 4.3.1.2, a correction factor is introduced to permit measurements of copper metallizations above 200 °C and reference is made to Annex A.2.

4.4 Parameters to be selected

- All subclauses have been given titles.
- Subclause 4.4.3 (Temperature range) has been changed to eliminate the requirement for determining the TCR over a range that includes the temperature at which the TCR is used to calculate joule heating or ambient temperature. An upper limit on the temperature range (180 ºC) is imposed for copper metallizations; this limit is suggested for aluminum metallizations.

5.1 Linear dependence

- The coefficient of simple determination, r^2, is used as an approximate indicator of linearity instead of the correlation coefficient, r.

5.2 Stability of resistance

- All subclauses have been given titles.
- In 5.2.2, correlation coefficient is replaced by coefficient of simple determination.
- Subclause 5.2.5 has been deleted because the standard now permits the use of the TCR at temperatures beyond the temperature range where the TCR was determined.

5.4 Wafer-level measurements

- All subclauses have been given titles.
- In 5.4.2, a sentence is added to caution reader that heat loss from the wafer can be affected by the placement of a probe card stage over the wafer, as when making electrical contact with the test structure.

5.5 Package-level measurements

- All subclauses have been given titles.

5.6 Thermal equilibrium

- Clause 5.6 has been expanded into three subclauses titled: Thermal response of wafer, Thermal response of package, and Automated test equipment.

5.7 Mean temperature of test line

- A sentence has been added to mention the effect of vias in the test line.

Annex B (informative) Differences between JESD33B and JESD33-A (cont'd)

5.9 Accurate voltage measurements

- This clause has been expanded and given a new title. The original title was "Thermal-EMF voltage".

5.13 Low-k dielectrics (New)

5.14 Dependence of TCR(T) on test structure processing and design (New)

8 Procedure for TCR(T_{ref}) measurement

- The titles for 8.3, 8.4, 8.5, and 8.6 have been modified slightly.
- Subclauses in 8.3, 8.5, and 8.6 have been given titles.
- In 8.5.2, the coefficient of simple determination is to be calculated instead of the correlation coefficient.

9 Procedure for measuring test-line temperature due to Joule heating

- The original title and intent of this clause was to measure the *increase* in the temperature of the test line. The intent is now to measure the temperature of the test line subjected to Joule heating. The title of clause 9.5 is also changed to reflect this change in focus. Other clauses have new titles, but the new titles do not change the intent and meaning of these clauses.
- In clause 9.5, the correction factor, F_{corr}, is introduced to permit temperature measurements of copper test lines at high temperatures where the dependence of the resistance on temperature is no longer linear.

10 Procedure for measuring ambient temperature with test line

- There are slight differences in the wordings of the clause titles. A note has been added.
- In clause 10.5, the correction factor, F_{corr}, is added for the same reason it was added in 9.5

11 Measurement of bias and precision

- Table 1 is added to summarize the results of an inter-laboratory experiment. A reference, [8], to a paper that describes this experiment has been added in the introductory paragraph.
- The subclauses of 11.1and 11.2 are now presented as a list with a few minor changes in the text.
- In 11.3, all clauses and subclauses have been given titles.

13 Additional optional information to report

- In 13.1 c) and in 13.2 b), the dimensions of any vias present is included.
- In 13.1 g) the report of the coefficient of simple determination is substituted for the correlation coefficient.

Annex B (informative) Differences between JESD33B and JESD33-A (cont'd)

14 References

- Updated citations for references [1] and [2] are used.
- Reference [3] becomes [4] and old references [4] and [5] are replaced.
- New references are: [3], [5], [6], [7], [8], [9], [10], and [11].

Annexes A and B (New).

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