

JEDEC STANDARD

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

JESD33B

(Revision of JESD33-A)

FEBRUARY 2004 (Reaffirmed: October 2012)

JEDEC SOLID STATE TECHNOLOGY ASSOCIATION



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

(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 °C, 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 [1], [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.

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

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

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 $TCR(T = 30^\circ\text{C})$ for aluminum and copper will be no larger than approximately $0.00414^\circ\text{C}^{-1}$ and $0.00389^\circ\text{C}^{-1}$, 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 ,

$$\text{TCR}(T) = \frac{1}{R(T)} \times \frac{\Delta R}{\Delta T} \quad (^\circ\text{C}^{-1}) \quad (1)$$

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 $\text{TCR}(T)$ 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:

$$R(T) = R(0) + S \times T, \quad (2)$$

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)

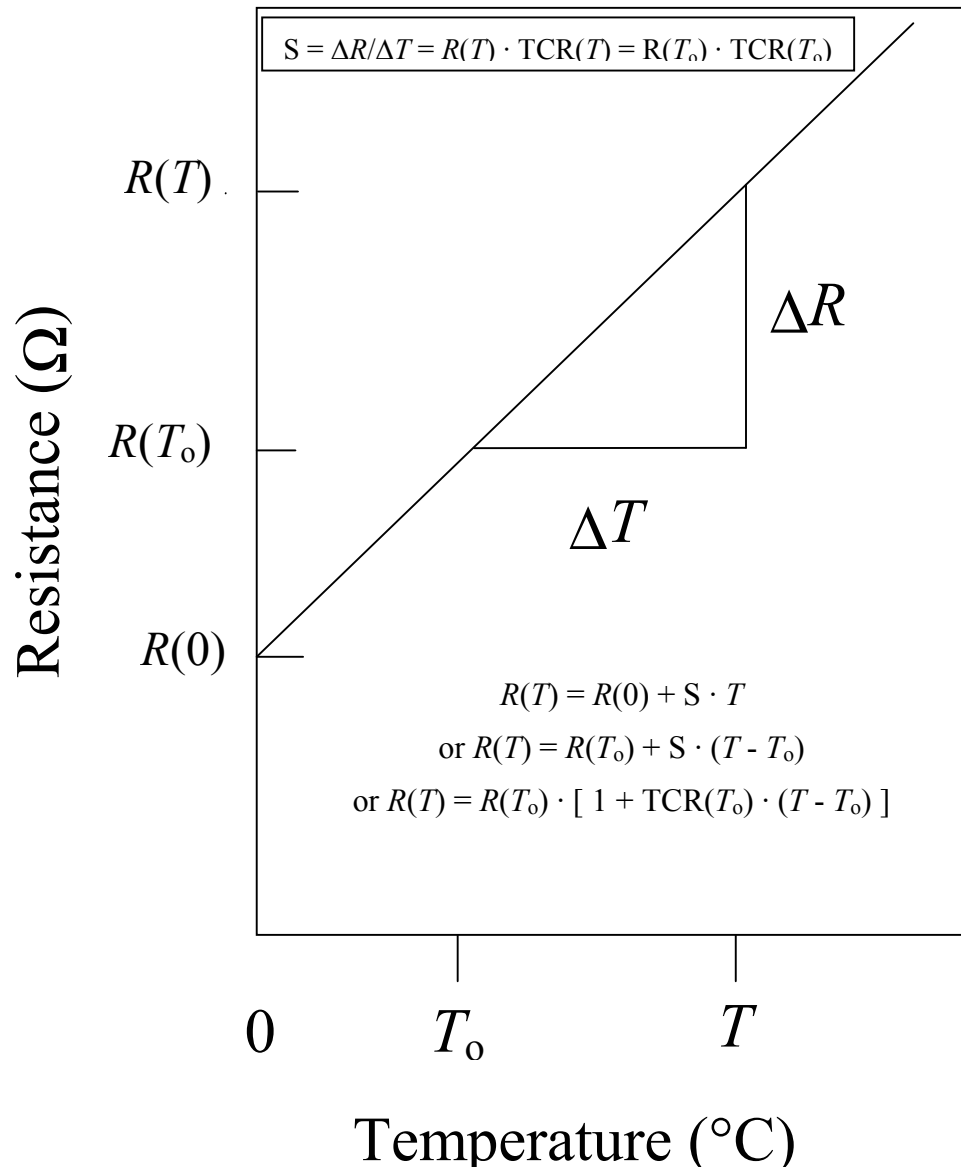


Figure 1 — Illustration of terms used in text on a plot of resistance versus temperature.

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 :

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

4.2.2 Intercept and slope

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

$$R(T) = R(T_0) \times (1 - TCR(T_0) \times T_0) + R(T_0) \times TCR(T_0) \times T \quad (4a)$$

where the intercept at $T = 0$ °C is

$$R(0) = R(T_0) \times (1 - TCR(T_0) \times T_0) \quad (4b)$$

and where the slope is

$$S = R(T_0) \times TCR(T_0). \quad (4c)$$

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

$$S = R(T) \times TCR(T) = R(T_0) \times TCR(T_0). \quad (4d)$$

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 :

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

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:

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

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:

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