IEC/PAS 62204

Edition 1.0
2000-11

Standard method for measuring and using the temperature coefficient of resistance to determine the temperature of a metallization line

PUBLICLY AVAILABLE SPECIFICATION

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

Reference number
IEC/PAS 62204

EIA/JESD33-A

EIA/JEDEC STANDARD

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

EIA/JESD33-A

(Revision of JESD33)

OCTOBER 1995

ELECTRONIC INDUSTRIES ASSOCIATION

ENGINEERING DEPARTMENT

NOTICE

EIA/JEDEC Standards and Publications contain material that has been prepared, progressively reviewed, and approved through the JEDEC Council level and subsequently reviewed and approved by the EIA General Counsel.

EIA/JEDEC Standards and Publications are designed to serve the public interest through eliminating misunderstandings between manufacturers and purchases, facilitating interchangeability and improvement of products, and assisting the purchaser is selecting and obtaining with minimum delay the proper product for his particular need. Existence of such standards shall not in any respect preclude any member or nonmember of JEDEC from manufacturing or selling products not conforming to such standards, nor shall the existence of such standards preclude their voluntary use by those other than EIA members, whether the standard is to be used either domestically or internationally.

EIA/JEDEC Standards and Publications are adopted without regard to whether their adoption may involve patents or articles, materials, or processes. By such action, EIA/JEDEC does not assume any liability to any patent owner, nor does it assume any obligation whatever to parties adopting the EIA/JEDEC Standards or Publications.

The information included in EIA/JEDEC Standards and Publications represents a sound approach to product specification and application, principally from the solid state device manufacturer viewpoint. Within the EIA/JEDEC organization there are procedures whereby an EIA/JEDEC Standard or Publication may be further processed and ultimately becomes an ANSI/EIA Standard.

Inquiries, comments, and suggestions relative to the content of this EIA/JEDEC Standard or Publication should be addressed to the JEDEC Executive Secretary at EIA Headquarters, 2500 Wilson Boulevard, Arlington, VA 22201.

Published by

© ELECTRONIC INDUSTRIES ASSOCIATION 1997
Engineering Department
2500 Wilson Boulevard
Arlington, VA 22201

INTERNATIONAL ELECTROTECHNICAL COMMISSION

STANDARD METHOD FOR MEASURING AND USING THE TEMPERATURE COEFFICIENT OF RESISTANCE TO DETERMINE THE TEMPERATURE OF A METALLIZATION LINE

FOREWORD

A PAS is a technical specification not fulfilling the requirements for a standard, but made available to the public and established in an organization operating under given procedures.

IEC-PAS 62204 was submitted by JEDEC and has been processed by IEC technical committee 47: Semiconductor devices.

The text of this PAS is based on the following document:	This PAS was approved for publication by the P-members of the committee concerned as indicated in the following document:
Draft PAS	**Report on voting**
47/1509/PAS	47/1541/RVD

Following publication of this PAS, the technical committee or subcommittee concerned will investigate the possibility of transforming the PAS into an International Standard.

An IEC-PAS licence of copyright and assignment of copyright has been signed by the IEC and JEDEC and is recorded at the Central Office.

1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, the IEC publishes International Standards. Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non governmental organizations liaising with the IEC also participate in this preparation. The IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of the IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested National Committees.
3) The documents produced have the form of recommendations for international use and are published in the form of standards, technical specifications, technical reports or guides and they are accepted by the National Committees in that sense.
4) In order to promote international unification, IEC National Committees undertake to apply IEC International Standards transparently to the maximum extent possible in their national and regional standards. Any divergence between the IEC Standard and the corresponding national or regional standard shall be clearly indicated in the latter.
5) The IEC provides no marking procedure to indicate its approval and cannot be rendered responsible for any equipment declared to be in conformity with one of its standards.
6) Attention is drawn to the possibility that some of the elements of this PAS may be the subject of patent rights. The IEC shall not be held responsible for identifying any or all such patent rights.

STANDARD METHOD FOR MEASURING AND USING THE TEMPERATURE COEFFICIENT OF RESISTANCE TO DETERMINE THE TEMPERATURE OF A METALLIZATION LINE

CONTENTS

Page

STANDARD METHOD FOR MEASURING AND USING THE TEMPERATURE COEFFICIENT OF RESISTANCE TO DETERMINE THE TEMPERATURE OF A METALLIZATION LINE

CONTENTS *(continued)*

Page

7 Ambient temperature controller

8 Procedure for TCR(T_{ref}) measurement

9 Procedure for measuring increase in test-line temperature due to joule heating

10 Procedure for measuring ambient temperature with test line

11 Measurement bias and precision

12 Required reporting

STANDARD METHOD FOR MEASURING AND USING THE TEMPERATURE COEFFICIENT OF RESISTANCE TO DETERMINE THE TEMPERATURE OF A METALLIZATION LINE

CONTENTS *(continued)*

Page

13 Additional, optional information to report

STANDARD METHOD FOR MEASURING AND USING THE TEMPERATURE COEFFICIENT OF RESISTANCE TO DETERMINE THE TEMPERATURE OF A METALLIZATION LINE

(From JEDEC Council Ballot JCB-95-11, formulated under the cognizance of JC-14.2 Committee on Wafer Level Reliability.)

1 Scope

This method is intended for determining the temperature coefficient of resistance (at a given reference temperature) of aluminum and aluminum-alloy 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 the reference temperature.

The method is intended for use only under time, temperature, and current-density conditions where the metallization resistivity is linearly dependent on temperature and where it does not suffer any irreversible changes. These conditions may be different for different metal alloys and different deposition and treatment processes.

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

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]. 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 K).
For example, an error of 5 °C in stress temperature introduces a 25% error in the sample estimate for t_{50} (at 150 °C and when the activation energy is 0.7 eV).

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.

The temperature coefficient of resistance of aluminum metallization is essentially dependent only on the residual resistivity whose magnitude is determined by departures from the structural order of pure, bulk aluminum that contribute to electron scattering [3]. As such, the temperature coefficient of resistance is a fundamental characteristic of the metallization.

3 Definitions

Metallization: a thin-film metallic conductor used to make electrical interconnects in a microelectronic integrated circuit.

Temperature Coefficient of Resistance, TCR(T): the fractional change in resistance per unit change in temperature at a specified temperature T,

$$TCR(T) = \frac{1}{R(T)} \times \frac{\partial R}{\partial R} \quad ({}^{\circ}C^{-1}), \qquad (1)$$

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

Test Line: a metallization line of specified dimensions, the length of which is defined by the locations of two voltage taps used to make Kelvin-type resistance measurements of the test line when two other terminals force a current through the line. (See 4.4.1.)

Test Structure: a passive metallization structure, which includes a test line, that is fabricated on a semiconductor wafer by procedures used to manufacture microelectronic integrated devices. *(See 4.4.1.)*

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(°C) can be given by:

$$R(T) = R(0) + S \cdot T, \qquad (2)$$

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.)*

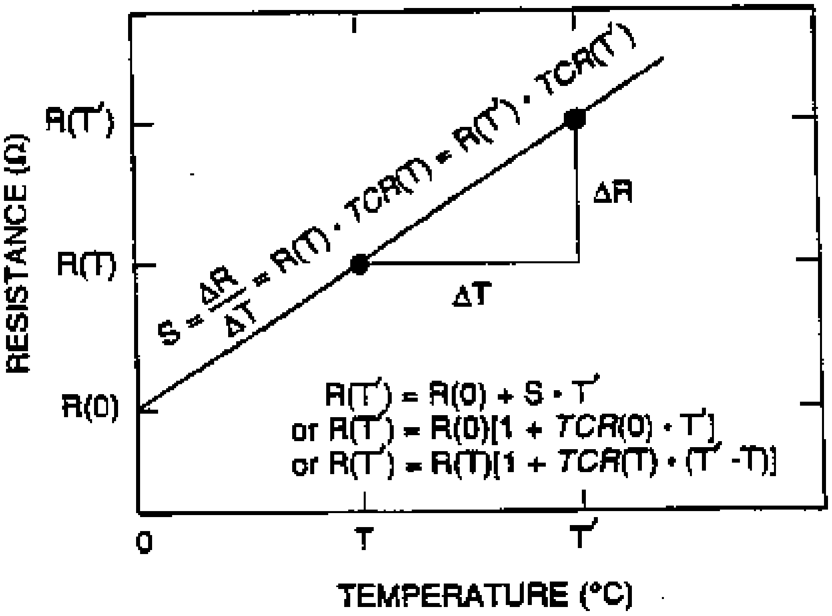

Figure 1 — Illustration of terms used in text on a plot of resistance versus temperature.

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 From the definition for TCR(T) (see section 3) and assumption 1 (see 4.1.1) the resistance of the test line at temperature T is related to the resistance at another temperature, T', by the temperature coefficient of resistance of the test line for temperature T:

$$R(T') = R(T) \bullet \{1 + TCR(T) \bullet (T' - T)\} . \qquad (3)$$

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

$$R(T') = R(T) \bullet \{1 - TCR(T) \bullet T\} + R(T) \bullet TCR(T) \bullet T' \qquad (4a)$$

to show that the resistance of the test line at 0 °C is

$$R(0) = R(T) \bullet (1 - TCR(T) \bullet T) \qquad (4b)$$

and that the slope of the resistance-versus-temperature line is

$$S = R(T) \bullet TCR(T) \bullet \qquad (4c)$$

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

$$S = R(T) \bullet TCR(T) = R(T') \bullet TCR(T') .$$

Equation 4d relates the product of the temperature coefficient of resistance and test-line resistance at one temperature, T, to that product for another temperature, T'.

4.2.3 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:

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

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.

4.2.4 The temperature coefficient of resistance at one temperature, T, is related to that at another temperature, T', by:

$$\mathrm{TCR}(T') = \frac{\mathrm{TCR}(T)}{1 + \mathrm{TCR}(T) \bullet (T' - T)} . \qquad (6)$$

4.3 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) a mean temperature increase 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 The temperature coefficient of resistance of the metallization at a preselected reference temperature, T_{ref}, is determined as follows:

4.3.1.1 Measure the resistance of the test line at four or more ambient temperatures, uniformly distributed over a preselected temperature range (see 4.4.3).

4.3.1.2 Determine the best straight-line fit of the resistance versus temperature data, using an unweighted, least-squares fitting procedure [5] 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 the resistance of the test line at temperature, T_{ref} from the values obtained for S and R(0) by using equation 2:

$$R(T_{ref}) = r(0) + S \bullet T_{ref} \qquad (7)$$

4.3.1.4 Calculate the temperature coefficient of resistance from equation 5:

$$\mathrm{TCR}(T_{ref}) = \frac{S}{R(T_{ref})} \qquad (8)$$

4.3.2 A mean value for the temperature increase, $T - T_a$, above ambient of the test line is calculated from the following equation when joule heating is present:

$$\overline{T} - T_a = \frac{R(\overline{T}) - R(T_a)}{R(T_{ref}) \cdot TCR(T_{ref})}, \tag{9}$$

where:

$R(\overline{T})$ is the measured resistance of the test line subjected to a stress current,

$R(T_a)$ is the measured resistance of the test line at ambient temperature, T_a, before the stress current is applied, and

$R(T_{ref})$ is the resistance of the test line at temperature, T_{ref}, to which the temperature coefficient of resistance is referenced.

4.3.3 The temperature, T, of the test-line is calculated from the following equation:

$$T = \frac{R(T) - R(T_{ref})}{R(T_{ref}) \cdot TCR(T_{ref})} + T_{ref} \tag{10}$$

where T_{ref} is the temperature at which the temperature coefficient of resistance is determined.

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

4.4.2 The stress current I, used to generate joule heating shall be selected and reported with the results of the measurements (see 9.4 and 13.2.5).

4.4.3 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 range should include the temperatures at which the temperature coefficient of resistance is to be used to determine joule heating or ambient temperature (see 5.2.5). 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. It is recommended that the maximum range be less than approximately 200 °C to avoid nonlinearity effects at the higher temperatures (see 5.1).

4.4.4 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 13.1.6.)

4.4.5 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

The linear dependence of the resistance of aluminum-based metallizations on temperature is approximated well by the dependence of pure, bulk aluminum [4], as revealed by Matthiessen's Rule [3]. The degree to which this dependence is linear can be characterized by the correlation coefficient of an unweighted, least-squares fitting procedure [5] of resistance-versus-temperature data. The published data [4] for the resistivity of pure, bulk aluminum versus temperature is characterized by a correlation coefficient of 0.99995 in the range of zero to 200 °C. The linearity of the change of metallization resistance with temperature is expected to be no better than this level. If the upper temperature limit is increased or if the range is shifted to higher temperatures, the linearity of the published data is less, as indicated by a reduction of the correlation coefficient to less than 0.9999. This departure in linearity will be reflected in a degradation in the linearity of the dependence of metallization resistance on temperature and the potential for reduced precision of the method.

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 Metallizations that have not been 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.

5.2.2 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 correlation coefficient, an error in the calculated value of the temperature coefficient of resistance, or both. It may be desirable to check for such changes when making significant changes in the temperature range and when testing significantly different metallizations. This may be done following a determination of the temperature coefficient of resistance by repeating the resistance measurement at the lowest temperature. The repeat resistance value should agree with the original one to within the repeatability of the measurement at that temperature.

5.2.3 Metallizations that are subjected to current-density and temperature stresses for sufficiently long periods of time during the test may undergo electromigration-induced changes in the resistivity and in the temperature coefficient of resistance. Measurement errors due to these factors can be reduced by minimizing the time that the test line has been subjected to high current-density stress before the measurement is made.

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

5.2.5 If the temperature coefficient of resistance is used to calculate joule heating or ambient temperature at a temperature beyond the temperature range within which the coefficient was determined, temperature-induced changes in the metallization (see 5.2.2) may occur which will introduce errors in these calculations.

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 nonuniformities and to variations of the wafer temperature.

5.4.1 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 The difference between the temperature 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.

5.4.3 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 nonuniformities and variations of the temperature in the environmental chamber (oven).

5.5.1 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 Variations of the temperature within the environmental chamber with time (as may be caused by thermal nonequilibrium 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.

For measurements performed on packaged specimens, it may take several minutes to achieve thermal equilibrium. For measurements on the wafer in contact with a temperature-controlled stage, the thermal response time is typically much less than a second. In either case, the thermal response of the test specimen can be determined by monitoring the variation of the test-line resistance with time after a constant-current stress has been applied.

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.

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 Thermal-EMF voltage

To avoid errors in the measurement of the resistance of the test line due to thermal-emf voltages, the mean of the resistances measured with both current polarities must be used to determine the resistance of the test line. In cases where the measurement current is large, such as in an electromigration stress test, the magnitude of the thermal-emf voltages will generally be only a small fraction of the test-line voltage. Then, there may not be a need to make resistance measurements with both current polarities.

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 before each contact with a test structure or at some other longer interval, 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. Periodic calibration checks of such sensors can help to avoid temperature-measurement errors.

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.

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.

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 Ambient temperature adjustment

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 $R(T_1)$

Determine the resistance, $R(T_1)$, of the test line.

8.3.1 Select a measurement current I_m for the test line that is not large enough to produce measurable joule heating in the metallization. (See note 1 and 5.3.)

> NOTE 1 — 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 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 the resistance $R_1(T_1) = V_1 / I_m$.

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

8.3.5 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 $R_2(T_1)$.

8.4 Determine R(T) 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 Analysis of R(T) 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 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 [5]).

8.5.2 Calculate-the correlation coefficient (see [5]). If the correlation coefficient is greater than 0.9990, proceed to 8.5.3. Otherwise, return to 8.1 or 4.4.3 to repeat the procedure with increased control and measurement sensitivity. (See 5.1, 5.2, 5.4 and 5.5.)

8.5.3 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 Calculate TCR(T_{ref})

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

8.6.1 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:

$$R(T_{ref}) = R(0) + S \cdot T_{ref} \ . \qquad (11)$$

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

$$TCR(T_{ref}) = \frac{S}{R(T_{ref})} . \qquad (12)$$

9 Procedure for measuring increase in test-line temperature due to joule heating

9.1 Determine ambient temperature of test line, T_a

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 $R(T_a)$

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

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

9.3 Calculate $R(T_{ref})$

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

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

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

9.4 Measure resistance R(T)

Measure the resistance of the test line, R(T), during the application of the stress current, I_s, selected in 4.4.2. (See 5.9.)

9.4.1 Apply stress current, I_s, to the test line and wait until thermal equilibrium has occurred before measuring the voltage, $V(_1)$, between the voltage taps of the test line. (See 5.4, 5.5, 5.6, 5.10, and 13.2.6.)

9.4.2 Calculate the resistance of the test line $R(T) = V(T)/I_s$ (see 5.9).

9.5 Calculate mean temperature increase $T - T_a$

Calculate the mean temperature increase, $T - T_a$, 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):

$$T- - T_a = \frac{R(T-) - R(T_a)}{R(T_{ref}) \bullet TCR(T_{ref})}$$

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

10 Procedure for measuring ambient temperature with test line

10.1 Apply measurement current, I_m

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 $R_1(T) = V_1/I_m$

10.3 Reverse measurement current

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 R(T)

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 temperature of test line

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

$$T = \frac{T(T) - R(T_{ref})}{R(T_{ref}) \bullet TCR(T_{ref})} + T_{ref} \, ,$$

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

11 Measurement bias and precision

Five laboratories and a reference laboratory took part in an interlaboratory 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. The following parameters of 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.

11.1 Summary

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

11.1.2 The sample estimate for the interlaboratory reproducibilty standard deviation for joule heating measurements is 0.14 °C, for a mean temperature increase of approximately 8 °C. The sample estimate for the within-laboratory repeatability standard deviation is 0.03 °C.

11.1.3 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.

11.1.4 An important source for variability in these measurements is 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.

11.1.5 Other sources for variability are related to measurements affected by temperature. One source is the making of measurements before thermal equilibrium has been established. Another source is 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

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 interlaboratory experiment.

11.2.2 To calculate each of the four sets of values 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 at the resistance of the test line at that temperature.

11.2.3 The measure used for the sample estimate of the repeatability standard deviation for TCR(0), $\Delta R/\Delta T$, and R(0) is the standard deviation of the four values divided by the mean, expressed in percent. The mean of the four sets of measurements of TCR(0), $\Delta R/\Delta T$, and R(0) were: $0.003592\ {}^{\circ}C^{-1}$, $0.1055\ \Omega/{}^{\circ}C$, and $29.376\ \Omega$, respectively. The standard deviations, as percents of these means, were 0.21%, 0.13%, and 0.09%, respectively.

11.2.4 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.

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

11.3 Between-laboratory precision and bias

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

11.3.2.1 The sample estimate of the reproducibility standard deviation of TCR(0) measurements from five laboratories is 2.5% . The TCR(0) values, as measured by the reference laboratory, ranged from 0.003362 $^{\circ}C^{-1}$ to 0.003592 $^{\circ}C^{-1}$ and have a mean of 0.003529 $^{\circ}C^{-1}$.

11.3.2.2 The sample estimates for the reproducibility standard deviation of R(0) and $\Delta R/\Delta T$ measurements are 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/°C to 0.1055 Ω/°C.

11.3.2.3 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. Another participating laboratory used an automated control and measurement system which did not permit thermal equilibrium to be established before making measurements and which led to temperature differences that were almost ten times that obtained by the other three laboratories.

11.3.2.4 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 Subsequent to the measurements of 11.3.1, each participating laboratory was sent a portable, battery-powered, surface-temperature measuring system to access 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 that is less than 0.2 °C.

11.3.3.1 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.

11.3.3.2 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 difference 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 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:

13.1.1 Identification of operator(s) of test,

13.1.2 Equipment used (see sections 6 and 7.),

13.1.3 Dimensions of test line used in test (see sections 3 and 4.4.1),

13.1.4 Nominal metallization alloy of the test line,

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

13.1.6 Temperatures selected in 4.4.4,

13.1.7 Correlation coefficient (from 8.5.2), and

13.1.8 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:

13.2.1 Level of measurement: wafer or package,

13.2.2 Dimensions of the test line (see sections 3 and 4.4.1),

13.2.3 Thickness and identification of any underlying and overlying layers and structures,

13.2.4 Ambient temperature T_a (from 9.1),

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

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

13.2.7 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

13.2.8 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:

13.3.1 Dimensions of the test line (see sections 3 and 4.4.1),

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

13.3.3 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

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

14 References

[1] F 1260-89 Standard Test Method for Estimating Electromigration Median Time-To-Failure and Sigma of Integrated Circuit Metallizations, Annual Book of ASTM Standards, Vol 10.04.

[2] JEDEC Document for the SWEAT Test (in preparation).

[3] N. F. Mott and H. Jones, The Theory of the Properties of Metals and Alloys, Dover Publications, Inc. New York, p. 286, 1958.

[4] Aluminum - Properties and Physical Metallurgy, John E. Hatch, Ed., American Society for Metals, Metals Park, Ohio, Table 4, p. 10, 1984.

[5] Dixon, Wilfrid J., and Massey, Jr., Frank J., Introduction to Statistical Analysis, McGraw-Hill Book Co., New York, 4th Edition 1984, Chapt. 11.

ISBN 2-8318-5480-6

9 782831 854809

CODE PRIX **M**

For price, see current catalogue

ICS 31.080.01

Typeset and printed by the IEC Central Office
GENEVA, SWITZERLAND