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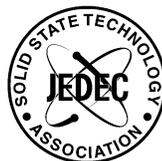
A procedure for executing SWEAT

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A Procedure for Executing SWEAT

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A PROCEDURE FOR EXECUTING SWEAT

FOREWORD

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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
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1. SCOPE

This document describes an algorithm for executing of the Standard Wafer Level Electromigration Accelerated Test(SWEAT) on computer controlled instrumentation. The algorithm described represents one approach to the execution of SWEAT. Development and employment of other algorithms may produce satisfactory accelerated electromigration test results.

This document does not address the design of SWEAT test structures. Users of this algorithm report it effective on both straight line and "bow tie" structures. The JEDEC electromigration work group, JC 14.2.2, is currently preparing a standard on SWEAT structures.

2. INTRODUCTION

SWEAT is an accelerated electromigration test performed on microelectronic metallization. This highly accelerated test was developed as a fast method for obtaining a measure of metallization quality and providing process control data to the semiconductor manufacturer. It is not a method for estimating the in-use lifetime of metallization.

This document presents an algorithm for executing SWEAT on computer controlled instrumentation. The algorithm is derived from published and unpublished literature. It provides little innovation beyond what is currently documented. The intent is to provide a complete description of a basic, functional, SWEAT algorithm that will allow a programmer to begin using an accelerated electromigration test with ease.

The SWEAT algorithm uses a feedback control loop to adjust the stress current applied to the metallization under test. The stress current is adjusted such that the temperature and current density of the structure maintain the estimated time to failure, derived from Black's Equation, at the selected target value.

3. APPLICABLE DOCUMENTS

ROOT, B., TURNER, T., "Wafer Level Electromigration Tests for Production Monitoring", IEEE/International Reliability Physics Symposium, Pg 100-107, 1985.

JEDEC Standard JESD33 "Standard Method for Measuring and Using the Temperature Coefficient of Resistance to Determine the Temperature of a Metallization Line"

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

4. DEFINITIONS

4.1 estimated time to failure (t_{FE})

The required time of applied stress to cause the test structure resistance to exceed the failure resistance, estimated by Black's Equation¹,

$$t_{FE} = AJ^{-N} e^{E_a/kT} \quad (1)$$

where: t_{FE} is the estimated time to failure (s)

A is an empirically determined constant, provided by the programmer.

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

N is the current density factor, usually 2.0, provided by the programmer.

E_a is the activation energy of the metallization, provided by the programmer (eV).

k is Boltzmann's constant ($8.62E-5$ eV/K).

T is the structure temperature (K).

4.2 failure resistance criterion (R_{FC})

The resistance, in ohms, at or above which the structure is considered to have failed.

4.3 initial resistance (R_I)

Structure resistance, in ohms, at initial temperature (T_I) and before the structure is subjected to joule heating by the SWEAT algorithm.

4.4 initial temperature (T_I)

Metallization temperature, in kelvins, at the measurement of R_I . This is the temperature of the structure before joule heating by the SWEAT algorithm.

4.5 temperature ratio (tempratio)

Tempratio is an optional parameter used to relate the ratio of the change in temperature of the narrow region of a "bow tie" SWEAT structure to the change in mean temperature of the total structure due to joule heating. An example tempratio is given by equation 2,

$$\text{tempratio} = \frac{N_{sn}}{N_{sn}^2 + N_{sw}^2} (N_{sn} + N_{sw}) \quad (2)$$

where: N_{sn} is the number of resistive squares in the narrow region

N_{sw} is the number of resistive squares in the tapered and wide region.

¹ BLACK, J. R., "Electromigration of Al-Au Alloy Films", Proc: International Reliability Physics Symposium, 1978, pp.233-240

Note that in the extreme case of a straight line structure N_{sw} is equal to 0 and the resulting temperature ratio is one. For a derivation of this tempratio, see Appendix A, DERIVATION OF A TEMPRATIO.

4.6 Temperature Coefficient of Resistance (TCR(T))

TCR(T) is the fractional change in resistance per unit change in temperature at a specified temperature T, as described in equation (1) of JEDEC Standard JESD33,

$$\text{TCR}(T) = \frac{1}{R(T)} \cdot \frac{\Delta R}{\Delta T} \quad (^\circ\text{C}^{-1}) \quad (3)$$

where: $R(T)$ is the resistance of the test line at temperature T ($^\circ\text{C}$).

4.7 reference temperature (T_{REF})

The temperature at which the TCR(T) is specified. Note that the reference temperature is not necessarily the temperature at which the structure resistance is measured but it is usually computed as described in JEDEC Standard JESD 33.

4.8 target time to failure (t_{FT})

t_{FT} is the desired value of the time for failure of the test structure, in seconds.

4.9 starting current density (J_S)

J_S is the current density in the narrow region of the structure at the initial application of the SWEAT stressing, in amperes per square centimeter.

4.10 Area (a)

a refers to the cross-sectional area of the narrow region of the structure, in square centimeters.

4.11 error band (B_E)

The error band is a boundary, in seconds, for the estimated time to failure (t_{FE}), centered around the target time to failure (t_{FT}), within which the SWEAT algorithm will not permit the feedback control loop to adjust the forcing current.

$$t_{FT} - B_E < t_{FE} < t_{FT} + B_E \quad (4)$$

4.12 time to failure (t_F)

The time, in seconds, at which the structure resistance equals or exceeds R_{FC} while the structure is under stress from the SWEAT algorithm.

4.13 resistance at failure (R_F)

R_F is the structure Resistance during the control cycle just prior to t_F , in ohms.

4.14 current density at failure (J_F)

J_F is the applied current density (A/cm^2) during the control cycle just prior to t_F , based upon the a .

4.15 temperature at failure (T_F)

T_F is the estimated temperature (K) of the narrow regions of the SWEAT structure during the control cycle just prior to t_F .

5. TECHNICAL REQUIREMENTS

5.1 Equipment Requirements

- (1) A programmable current source capable of supplying sufficient current density to accelerate the electromigration failure of the metallization. Typically, current density of 10^7 amperes per square centimeter or greater is sufficient. Minimum force resolution of 12 bits, or 3.5 digits, is recommended.
- (2) A digital voltmeter capable of measuring the expected voltage magnitudes. Typically 10 volts or greater is sufficient. Minimum measure resolution of 12 bits, or 3.5 digits is recommended.
- (3) A computer controller. The computer provides a feedback control system. It controls the input current to the metallization under test, based upon discrete time measurements provided by the voltmeter and computations directed by the SWEAT algorithm.

5.2 General System Recommendations

The system should be capable of executing one control cycle with a period short enough to provide resolution of better than 1% in determining the time to failure. It should also provide sufficient feedback for effective control. A control cycle time shorter than 50 ms is not recommended. Test executions with a control cycle time of less than 50 ms have been observed to exhibit excessive failure time. This phenomena is caused by the control algorithm reducing the applied current density so rapidly that the failure condition is not established before the maximum test time is reached.

The optimal cycle time can be determined empirically for the metallization under test and may be longer than 50 ms.

Data acquisition times of less than 50 ms can be used to provide more complete data on the structure characteristics during transients. This data can be gathered by performing measurements without allowing control, as described by the algorithm, based on those measurements.

5.3 Test Configuration

Due to the typically high current requirements for SWEAT, four-wire Kelvin connection to the structure is required.

6. THE SWEAT ALGORITHM

6.1 Description of SWEAT

SWEAT uses a feedback control loop to adjust the stress current applied to the metallization such that temperature and current density of the structure maintain the target time to failure within a programmed error band. Figure 1 on page 6 describes the feedback control loop for computer controlled instrumentation.

Current is forced through the structure to achieve and then maintain the estimated time to failure within the error band of the target time to failure. The current density initially begins at a low value to ensure the device is not overstressed. A starting current density (J_S) is multiplied by the area (a) of the narrow region of the SWEAT structure to provide the starting current. Then the feedback control algorithm (described in Figure 1) operates to bring the current density to a level such that the estimated time to failure converges to the target time to failure within some error band. This action of the feedback control loop is called the initial settling period. Immediately upon completion of the initial settling period, the failure resistance R_{FC} is computed by multiplying the structure resistance by an empirically derived multiplication factor. By computing R_{FC} after settling, the failure criterion is based upon the heated structure resistance rather than the ambient temperature resistance. The multiplication factor chosen should reflect the expected resistance of the structure when the metallization opens due to electromigration.

After initial settling, the feedback control algorithm acts to maintain the estimated time to failure within the allowed error band as electromigration changes the resistance of the structure. Occasional changes in the estimated time to failure may fall outside the error band. The feedback algorithm will operate to bring the estimated time to failure within the error band. Finally, the resistance should quickly exceed the failure resistance. This is reflected, through the estimation of structure temperature, as a rapid decrease in estimated time to failure. The test is then terminated and the results logged.

6.1.1 SWEAT Characteristics

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

Settling period	Less than or equal to 10 percent of the target time to failure or at least 1 second. Settling period of less than 1 second may cause the t_{FE} to overshoot t_{FT} , overstressing the structure and invalidating the test.
Estimated time to failure	Must not be less than target time to failure during the initial settling time to prevent overstress of the structure.
Typical current density range	1.0E+7 to 3.0E+7 A/cm ²
Maximum feedback control time	200 ms so that the test has reasonable accuracy and sufficient control.
Minimum feedback control time	50 ms so that the control loop does not respond faster than the electromigration, reducing the current density such that the structure resistance never exceeds R_{FC} .
Typical starting current density	7.5E+6 A/cm ² so that the test does not start at current density sufficient to overstress the structure. Program J_S high enough to allow fast settling at the target time to failure, and low enough so that no overstress of the structure occurs.

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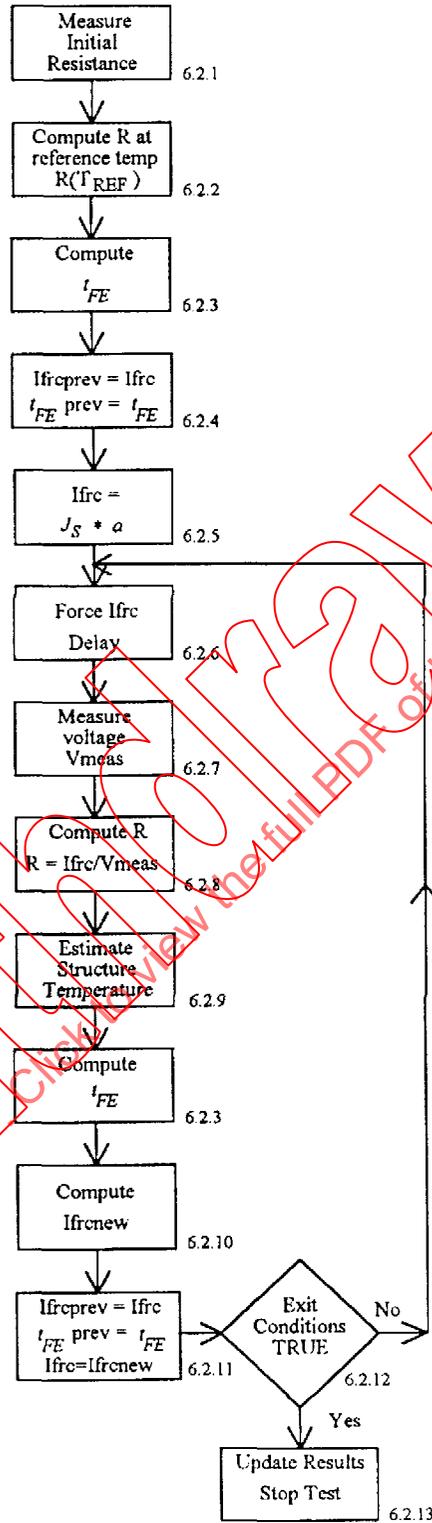


Figure 1
The SWEAT Algorithm.

6.1.2 Example SWEAT execution

Figure 2 illustrates a typical SWEAT execution.

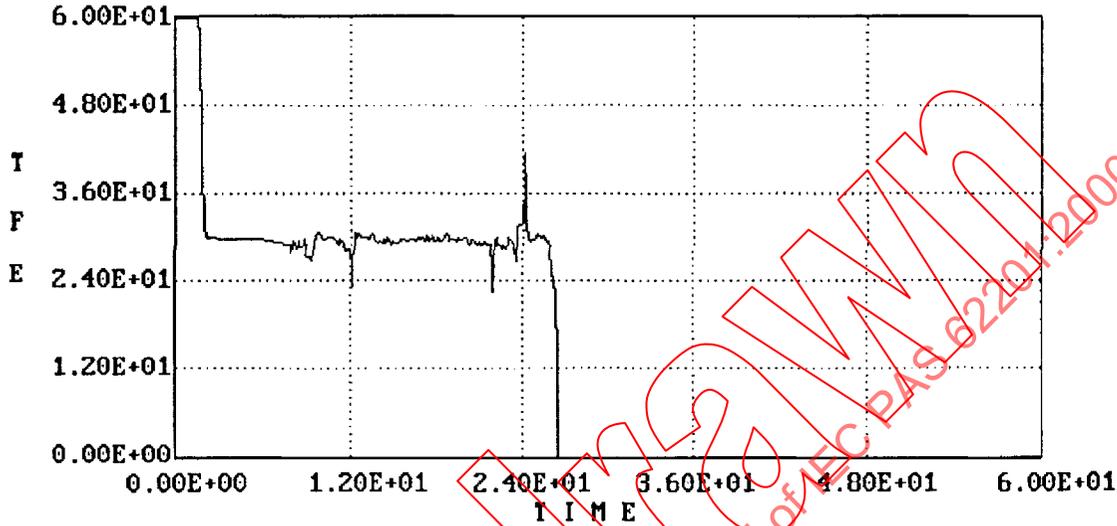


Figure 2
 t_{FE} versus Time for an example SWEAT execution.

The test was started with the following input values:

Parameter	Value	Parameter	Value
R_{FC} multiplication factor	1.5	T_I	25°C
tempratio	0.483	TCR(T)	0.0035 °C ⁻¹
T_{REF}	25°C	t_{FT}	30.0 s
J_S	1.0E+6 A/cm ²	B_E	1 s
a	4.0E-9 cm ²	A	1.5E+6 s A ² /cm ²
N	2.0	E_a	0.64 eV

The initial resistance was measured as 23.3 ohms. As the test starts at low current density, the estimated time to failure is out of scale. The actual value of t_{FE} started at a value of the order of 1.0E+5. The control loop increased the applied current until t_{FE} converged to the target value of 30 seconds. As the test progresses, fluctuations of t_{FE} outside of the error band are compensated for by the control loop.

Finally the structure fails at 26.4 seconds. t_{FE} goes toward zero at failure because the large increase in resistance is interpreted by the algorithm as a large increase in temperature.

6.2 Explanation of SWEAT flow chart in figure 1

6.2.1 Measure the initial resistance R_I

To measure R_I , use a current density that is sufficiently small so that joule heating is negligible. To determine if joule heating is negligible, halve the current and remeasure the resistance. If no significant change in resistance is noted by doing this, the original current used is acceptable. See 7.3 regarding interferences in establishing the initial resistance and temperature.

6.2.2 Compute R at the reference temperature $R(T_{REF})$

Because the estimation of structure temperature computation requires both the temperature coefficient of resistance and the structure resistance at reference temperature, it is necessary to compute the structure resistance at the reference temperature.

From JESD33 equation (3) 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 :

$$R(T') = R(T) \cdot \left\{ 1 + TCR(T) \cdot (T' - T) \right\} \quad (5)$$

This equation allows the determination of the resistance at a temperature if the temperature coefficient of resistance for that temperature is known and the resistance is known at any other temperature. Solving this relation for the resistance at temperature, T , yields:

$$R(T) = \frac{R(T')}{1 + TCR(T) \cdot (T' - T)} \quad (6)$$

In this application, the ambient temperature, resistance at ambient temperature, and temperature coefficient of resistance at the reference temperature, as defined by JEDEC Standard JESD33 are known. R_I is measured at a known ambient temperature typically determined by a hot chuck. This equation expressed in the context of our use becomes:

$$R(T_{REF}) = \frac{R_I}{1 + TCR(T_{REF}) \cdot (T_a - T_{REF})} \quad (7)$$

where: T_a is the ambient temperature of the structure.

6.2.3 Compute the t_{FE} as defined in 4.1

The estimated time to failure is derived from Black's equation, which models the median failure time of a statistically significant sample of intrinsic electromigration failures. The procedure applies this statistically derived model to the individual structure under test. While it is not physically accurate to apply a median failure time to an individual structure, the methodology has proven effective in controlling this highly accelerated test. The term *estimated* time to failure is carefully chosen to express that the

computation represents a statistically-based estimation, not a physically-based determination, of a particular structure's failure time.

No correlation is implied between this accelerated test and conventional lifetime testing, although Black's equation is used to control the execution of SWEAT.

6.2.4 Store the force current and t_{FE}

The feedback control algorithm will compute the force current by linear extrapolation. The force current used to measure R_I and the resulting t_{FE} are stored to initialize the control loop for the first linear extrapolation.

6.2.5 Compute the starting current

The force current (I_{FRC}) is initialized by multiplying the programmed starting current density, J_S , by the a .

6.2.6 Force the current and delay

This is the first logical block of the feedback control loop. Force the value of I_{FRC} that was determined from the starting current density or the linear extrapolation of the control loop.

The instrumentation may have a feedback control cycle time that is too fast for an effective SWEAT implementation. Feedback control cycle times faster than 50 ms are not recommended. An optional delay can be provided for in this step of the algorithm to slow the feedback control cycle time. See 7.2.

6.2.7 Measure the voltage

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

6.2.8 Compute the Resistance

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

6.2.9 Estimate the Structure Temperature

From JESD33 equation (9) the mean value for the temperature increase above ambient, $\bar{T} - T_a$, of the test line is calculated from the following equation when Joule heating is present:

$$\bar{T} - T_a = \frac{R(T) - R(T_a)}{R(T_{REF}) \cdot TCR(T_{REF})} \quad (8)$$

In the context of our use this equation becomes:

$$\bar{T} - T_a = \frac{R - R_I}{R(T_{REF}) \cdot TCR(T_{REF})} \quad (9)$$

where: \bar{T} is the mean temperature of the structure.

T_a is the ambient temperature.

R is the structure resistance as computed in 6.2.8.

R_I is the initial structure resistance as defined in 4.3.

$R(T_{REF})$ is the structure resistance at the reference temperature as computed in 6.2.2.

$TCR(T_{REF})$ is the temperature coefficient of resistance as defined in 4.6.

Due to the geometry of the "bow tie" SWEAT test structure, the mean value for temperature can optionally be corrected to provide a better estimation of the temperature of the narrow region by multiplication of the temperature increase above ambient by a temperature ratio. The relation for computing temperature increase of the narrow regions of the structure above ambient, when using the optional temperature ratio adjustment, is:

$$T_n - T_a = \frac{R - R_I}{R(T_{REF}) \cdot TCR(T_{REF})} \cdot \text{tempratio} \quad (10)$$

where: T_n is the estimated temperature of the narrow regions of the SWEAT structure.

tempratio is the ratio of the change in temperature of the narrow region of the SWEAT structure to the change in mean temperature of the total structure as defined in 4.5.

The relation for estimating the structure temperature is then:

$$T_n = \frac{R - R_I}{R(T_{REF}) \cdot TCR(T_{REF})} \cdot \text{tempratio} + T_a \quad (11)$$

The tempratio is effectively 1.0 when no temperature adjustment is used.

The algorithm attributes all change in resistance of the structure to thermal effects. This assumption is valid during the initial settling period. After the initial settling period, electromigration should be a significant cause of resistance change. This algorithm does not compensate for resistance change due to electromigration. Rather, it assumes that change in resistance is due only to change in temperature.

The algorithm, in using this example tempratio, assumes a very simple thermal model for the structure. The model assumes linear heat flow from the structure in one dimension, based on the estimated power dissipated in a section of the structure. It does not model thermal conduction from the narrow region to the wide region, or to surrounding material (substrate, passivation, etc.). The estimation of temperature may not be the actual temperature of the structure in the narrow region.

6.2.10 Compute the new force current

Apply the method described in Figure 3 to compute the new force current. Compute a new force current only if t_{FE} is outside of the error band (B_E).

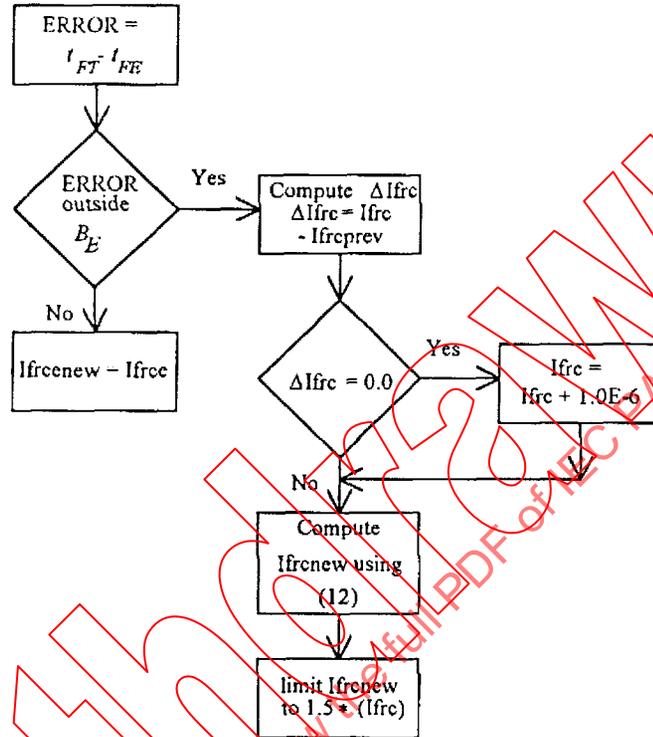


Figure 3
Computing the New Force Current.

Compute the new force current by linear extrapolation, based on the change in t_{FE} caused by the last change in the force current. During the initial settling period, a change in t_{FE} is caused by a temperature change due to a change in the force current. After the initial settling period, excursions of t_{FE} away from the target are primarily due to electromigration rather than a change in forced current. Regardless of the mechanism that causes a change in t_{FE} , calculate the new current to force by linear extrapolation. The new force current, I_{frcnew} , is determined by calculating the required change in current, based on the change in t_{FE} resulting from the last change in current, and adding that value to the present current.

$$I_{frcnew} = I_{frc} + (t_{FT} - t_{FE}) \left(\frac{I_{frc} - I_{frcprev}}{t_{FE} - t_{FEprev}} \right) \quad (12)$$

where: I_{frcnew} is the next current to force.

I_{frc} is the presently forced current.

$I_{frcprev}$ is the current forced during the previous iteration of the control loop.

t_{FEprev} is the estimated time to failure during the previous iteration of the control loop.

This provides the magnitude of the new force current. Limit the magnitude of the new current to 1.5 times the presently forced current to prevent over-stressing of the structure.

After the initial settling period, changes in t_{FE} are due to a change in resistance, not a change in forced current. Under this condition, arbitrarily set the change in forced current to 1.0E-6 ampere when a change in t_{FE} is detected to prevent a zero condition in the linear extrapolation computation of the new force current. The amount of 1.0E-6 ampere is chosen arbitrarily as a value that will prevent a multiplication by zero ($I_{frc} - I_{frcprev}$) without a large perturbation of the control loop.

6.2.11 Update the variables

Store the present values of the force current and estimated time to failure for use in the next control loop iteration.

6.2.12 Determining if exit conditions are TRUE

Use the method described in Figure 4 to determine if the exit conditions are true. To determine if exit conditions are true, first determine if the initial settling period has been completed. The initial settling period is complete at the first occurrence of t_{FE} inside the error band. At the first occurrence of t_{FE} inside the error band, the failure resistance is set by multiplying the measured resistance of the structure by an empirically determined multiplication factor. The upper bound of the multiplication factor should be 200 percent. Typical values are 10 to 30 percent.

Before the initial settling period, the resistance of the structure is not used as a failure condition. In summary, exit conditions are TRUE if any of the following is true:

- (1) R_{FC} has been set and the current structure resistance is greater than or equal to R_{FC} . This is the expected exit condition for the test. The structure resistance has increased such that the resistance is greater by a programmer-determined factor than the resistance just after initial settling.
- (2) Total testing time has expired.
- (3) A new force current has been computed which is larger than the current limit of the power supply.
- (4) Voltage compliance of the source has been reached.

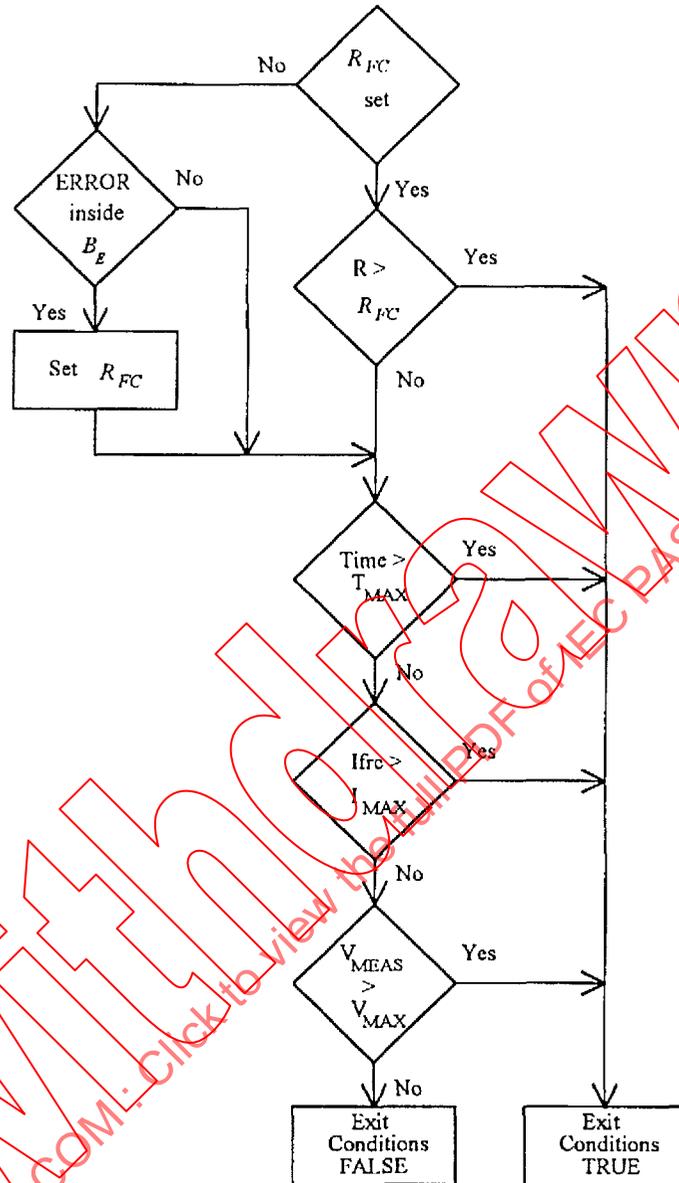


Figure 4
Determining if EXIT conditions are TRUE.

6.2.13 Update Results, Stop Test

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

Required results:

Time to failure (t_F), see 4.12. Should the test exit for conditions other than the structure resistance equaling or exceeding R_{FC} , consider reporting a value outside of valid test limits.

Optional Results:

Resistance at Fail (R_F), see 4.13.

Current Density at Fail (J_F), see 4.14.

Temperature at Fail (T_F), see 4.15.

The initial settling time, see 6.2.12.

The test status. Test status indicates the exit condition that caused the test to terminate. Report for test status the number of the exit condition that caused the test to terminate, as enumerated in 6.2.12.

7. Interferences**7.1 Thermal conduction to surrounding structures**

Due to the simple thermal model employed in the derivation and use of the example tempratio, the effectiveness of the test can be impacted by material surrounding the metallization under test. Metallization over thin oxide or close to heat sinking material can have considerable impact on SWEAT results.

7.2 Feedback control time and sampling

Section 5.2 states that the feedback control time should be no less than 50 ms. Based primarily on experience, 50 ms was considered the minimum time the control loop could be expected to operate and not have a response time less than the electromigration voiding. Feedback control times much faster than 50 ms have been observed to allow the control loop to reduce the current density so that the structure never completely fails.

Acquisition or sampling times faster than 50 ms have been used to characterize transient responses of the structure. But control time should be bounded by 50 ms regardless of the data acquisition rate.

7.3 Control of ambient temperature

Testing of multiple structures over a wafer can have a heating effect such that structures tested at the beginning of the wafer have a different initial temperature than structures tested at the end. In addition, many laboratory environments exhibit ambient temperature ranges as wide as 10°C during a short period. Such variance in the initial temperature has been observed to have an effect on the distribution of SWEAT results. Temperature control by means of a hot chuck or similar apparatus, or a determination of the initial temperature for each structure is recommended to avoid this source for variation in the test results. A hot chuck can be used to control the temperature at a moderate level above ambient such that the initial temperature variability is reduced.

7.4 Four-wire Kelvin test configuration

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