Isothermal Electromigration Test

The Isothermal test is used to determine the relative rate of electromigration in a metal line at a specified stress temperature. Electromigration is the preferential self diffusion of metal atoms due to the impact of a high density of conducted electrons. Thus the rate of electromigration is a function of the applied stress and the vacancy concentration in the metal line. The vacancies are concentrated around grain bourdries, at any free surface or at any interface between different metal layers. These provide three different sub-mechanisms referred to grain boundary diffusion, surface diffusion or interface diffusion respectively. The test is designed to apply a constant stress condition and to measure the rate of metal line resistance change due to electromigration. This rate of resistance change will be proportional to the vacancy concentration. The vacancy concentration will be a function of the metal processing, so this is a very sensitive way to monitor physical characteristics of the metal lines that are difficult to monitor any other way.

The important stress parameters are the temperature and the current density. This test induces a temperature in the metal line by joule heating at a high current density. The temperature induced by the current can be measured by measuring the change in resistance of the metal line as a function of the forced current. If the metal line TCR (temperature coefficient of resistance) is known, and the ambient temperature is known, then the line temperature can be easily extracted from the change in resistance of the line.

$$T = T0 + [(R / R0) - 1]/TCR$$

Where: T is the line temperature heated by joule heating
T0 is the ambient temperature
R is the line resistance heated by joule heating
R0 is the original line resistance measured at low current
TCR is the temperature coefficient of resistance (%/degree C)

The test ramps up the current while monitoring the change in resistance of the line. When a current is found that will induce the correct temperature in the line, either the current is held constant at this value, or the power provided to the line is held constant (depending on selected option). The resistance of the line as a function of time is then monitored. The test is terminated when the line's resistance has changed by more than a specified percent from the value measured when the stress conditions were held constant, or when a maximum stress time has been achieved. If the test can then verify that the line has opened by a measurement of the line's resistance at a low current again. If the line reaches the specified percent change in resistance, then the time to failure is the most important parameter. If the line does not fail during the stress, then the percent change in resistance is the most important parameter recorded.

Inputs:

Parameter	Default Value
1. Stress Temperature (Ts)	250 C
2. Maximum Stress Time	60 seconds
3. Constant I or Constant Power	Constant Power
4. Voltage Limit	10 volts
5. Line Width	3 u
6. Line Thickness	0.5u
7. Current for Initial R measurement	1mA/sq. micron
8. Current Limit	200mA
9. TCR	0.38%/degree C
10 Ambient Temperature (degrees C) (T_0)	25 degrees C
11. Failure Criteria (% change in resistance)	10%
12. Record R vs. t data yes/no	no
13. Force High Pin Number	
14. Measure High Pin Number	
15. Force Low Pin Number	
16. Measure Low Pin Number	

Outputs:

1. Initial Resistance (ohms) (output 2E21 if the line resistance is too high: hits voltage limit trying to force I)
2. Time to failure (seconds) (output 1E21 if the line does not fail during the stress, 2E21 if the test conditions could not be achieved, 3E21 if the desired stress temperature could not be controlled)
3. Current required to achieve Desired stress temperature.
4. Percent Change in resistance caused by Stress (%) (output 1E21 if the line is open: hits voltage limit trying to force specified I)

Test description:

1. Force Specfied “current for initial R measurement” through the Force High pin with the Force Low pin grounded. Delay for 10ms then measure voltage between the measure high and measure low pins (one line cycle integration). Calculate Ro = V/I. Record this as the “initial resistance”. Record 2E21 as the value for this measurement if the specified voltage limit is hit while trying to force this current. Terminate the test with values of 2E21 recorded for the other output variables if this occurs.
2. Force a current equal to a current density of 50mA per square micron of cross sectional area based on the input line width and line thickness. Delay for 10ms then measure the voltage between the measure low and measure high pins (one line cycle integration).
3. Calculate the resistance of the line at this stress condition (R2 = V2/I2), then calculate the change in resistance (R2 – R0). If this difference is greater than 3.8% of Ro, then calculate the temperature of the line at this stress condition ($T = T_0 + [(R2 /R0) – 1]/TCR$). Then calculate the thermal resistance ($Tr = (T - T_0)/(V I)$) (degree C/watt). If the change in resistance is not greater than 3.8%, then increase the forced current by 10% and measure the resistance again. Repeat this loop until the resistance does exceed 3.8% or the voltage limit is hit. If the voltage limit is hit, output 2E21 for the last three outputs and terminate the test.
4. Force a current calculated to provide the desired stress temperature

   I = the square root of $(Ts - T_0)/\{Tr\ Ro\ [1 + TCR\ (Ts - T_0)]\}$

   Measure the voltage drop across the metal line again and calculate the resistance and temperature just like in the previous step. Compare the measured line temperature to the desired line temperature. If the desired line temperature is within 0.5 degrees of the specified line temperature, then delay for another 30ms and measure the voltage drop again. If the measurement is within 0.5 degrees of the specified stress temperature then record this value as the third output parameter. If either or both of the two temperature measurements show a reading that is off from the specified value by more than 0.5 degrees C, then calculate the thermal resistance (Tr) and the next stress current again, just as was done in steps 3 and 4. If you can not reach within +/- 0.5 degrees after two adjustments, then check to see if we are within 2% of the desired change in temperature. If the line temperature is within 2% of the requested line temperature (e.g. wanted 225 C but achieved 220.5 C) then continue the test. Otherwise, output 3E21 for this parameter and 2E21 for the last two parameters.
5. Once the stress current has been achieved continue with one of the two options:

   A. Force a constant current at this value for the rest of the test

   B. Calculate the power (Power = $I^2 R$) and adjust the current to maintain a power that is within 1% of the measured current when the initial stress temperature is achieved. Each time a resistance measurement is made, the stress current should be recalculated.
6. While the current or power is being forced, the resistance of the line will be measured repeatably with a delay that starts at 1 ms. then increases by a factor of 1.1 each time the measurement is made. Each measurement will be integrated over one line cycle. If the delay gets up to 1/100 of the maximum stress time then do not let it exceed this delay between measurements. Each time the resistance is measured, the clock will be read and a time on stress will be calculated and recorded associated with the subsequent resistance measurement.
7. Each time the resistance is calculated compare it to the resistance measured the first time the stress conditions were found. If the change in resistance exceeds the “Failure Criteria”, then terminate the stress and record the time on stress as the “time to failure”. If the voltage limit is reached during this stress then terminate the stress and report the time on stress as the “time to failure”. If neither of these stress conditions are reached, then terminate the stress when the maximum stress time is reached. You must check to see if the calculated delay will take you beyond the maximum stress time each time the delay between measurements is calculated. If the delay will take you beyond the maximum stress time, then calculate the delay that will accomplish the maximum stress time.
8. When the stress is terminated, measure the resistance of the line just as was done in step 1 above. If the line reached the voltage limit during the stress above and reaches the voltage limit again in this stress, then record a

value of 1E21 as the "percent change in resistance caused by stress". If a valid resistance is measured, then calculate the percent change in resistance from the resistance measured in step 1 above and report this as the "percent change in resistance caused by the stress".

9. Open all relays and drive all SMUs to zero volts then delay for 20ms. Exit the test routine.

4 terminal resistance measurements with an SMU.

The four terminal resistance measurement requires three SMUs and the ground unit. The ground unit is connected to the force low terminal. The first SMU is connected to the force high terminal. This SMU will be used to force the specified stress current. The second SMU will be connected to the Measure high terminal. The third SMU will be connected to the Measure low terminal. The two SMUs connected to the measure terminals will force zero current (actually a small current like 0.1nA) and measure voltage. This will essentially measure the voltage induced at that measure terminal by the current source.

However, for really accurate measurements, it is often necessary to measure the calibration difference between the two SMUs. This can be done by connecting the ground unit to the force low terminal while nothing is connected to the force high terminal. The two other SMUs are then connected to the two measure terminals, and a voltage measurement is made. This should measure zero volts for each of the two SMUs. However, it is likely that a small difference in the measured voltage will be seen on each of the two SMUs. The difference between these two readings will be the "offset" voltage. Generally, the offset is measured at the start, before the force high terminal is connected to an SMU. For each measurement after that, the offset is subtracted from the calculated voltage difference to obtain the true voltage difference.

There is also a potential problem with thermal emf. If different metals are used in the test structure, then there will be a small potential difference generated by this contact. This voltage will increase with the temperature. This will cause an error in the measured resistance. This can be significant if a low resistance metal line is used. If there is no temperature change, then the offset voltage should take care of the thermal emf. However, if there is a temperature change (as there is in the isothermal test), then the original offset voltage measurement will not be able to extract the thermal emf as it will change with the temperature. In most designs this will not be an issue. For instance, if a thermal emf of +0.05 volts is generated at a certain temperature due to a tungsten via connected to an Al metal line, it is likely that there will be an identical via at the other end of line. This connection will supply a thermal emf that is equal, but opposite in direction to the thermal emf at the first end (-0.05V). Thus, they will cancel out as long as the design is symmetrical and two ends are at the same temperature.

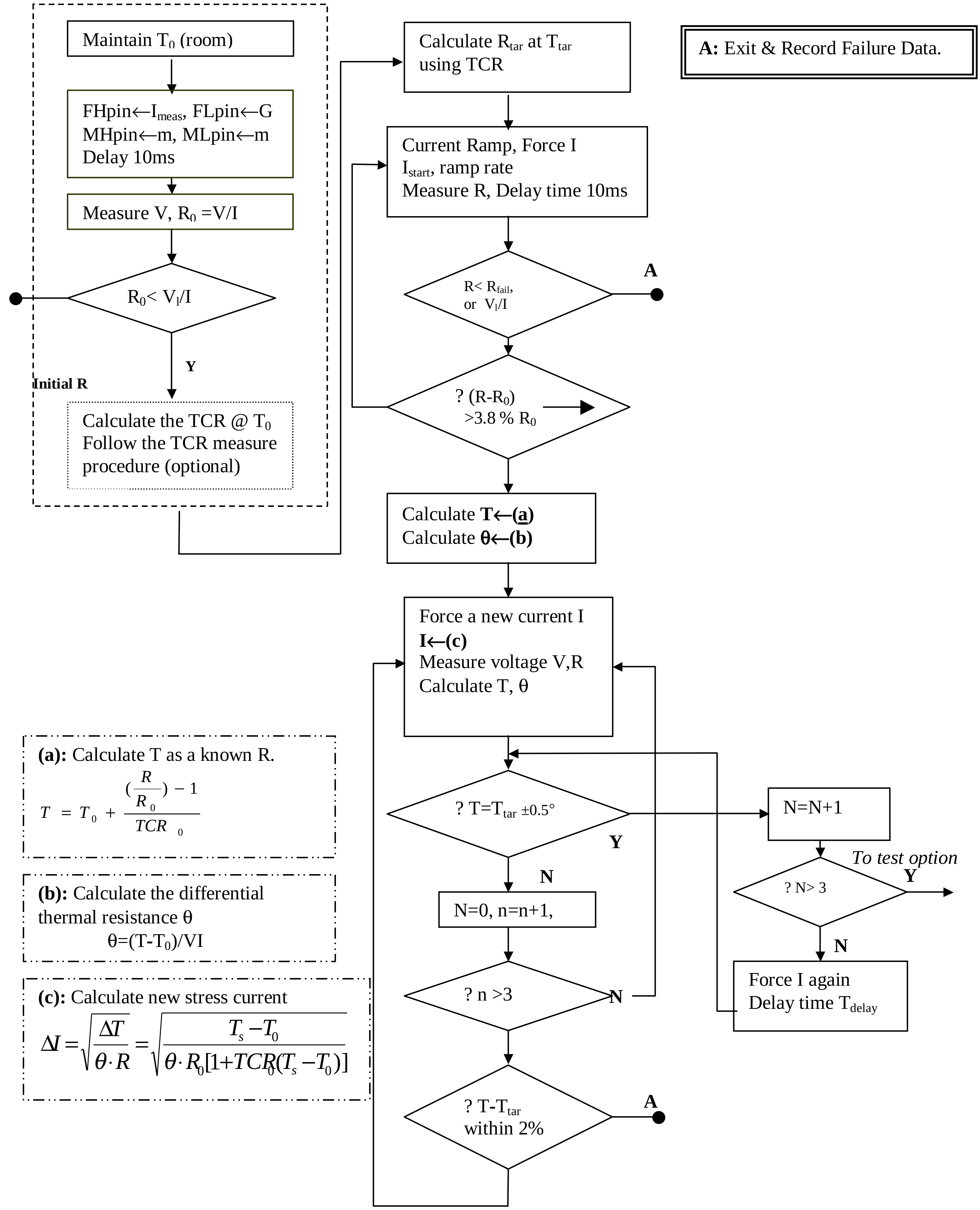
However, if symmetry can not be assumed, then it is necessary to force positive current and measure the voltage drop, then force negative current and measure the voltage drop again. If there is an unbalanced thermal emf, it will add to the voltage drop across the structure in one direction and subtract from it in the other current direction. Taking the average of the absolute value of the two measured voltages will provide the true voltage drop across the structure with no thermal emf effect.

Input Parameters:

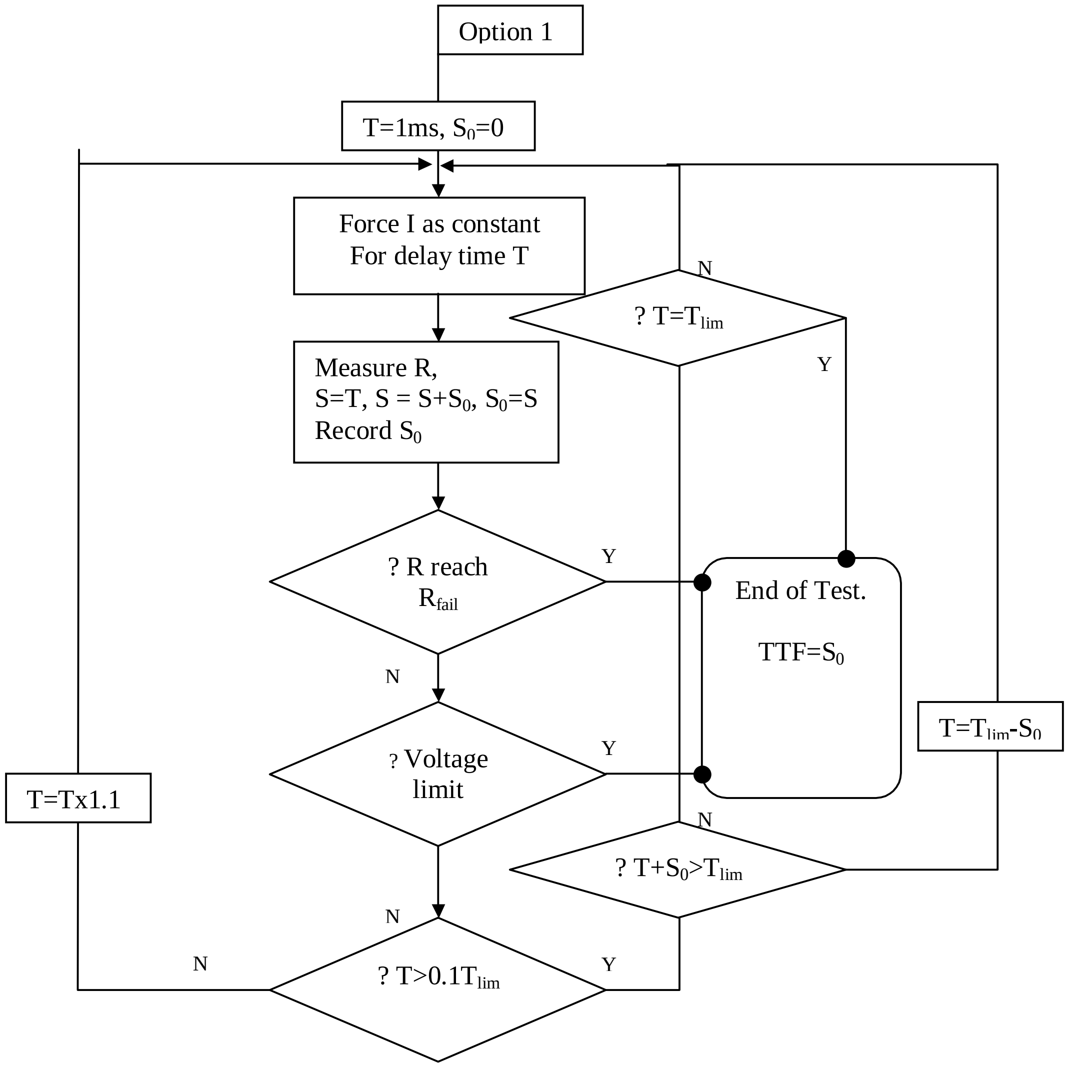
T_0	Ambient temperature- typically set as 0 or room temperature	25°C
T_{tar}	Target temperature	250°C
I_{meas}	Measurement current – non-Joule-Heating condition current	1mA/µm^2
I_{stress_Start}	Force current start	50mA/µm^2
Ramp rate	Increase rate of force current ramp	10%
T_{delay}	Force measure and control loop delay.	10ms
T_{main}	Time for control of stress current (Maintaining T_{tar} module)	3s
R_{fail}	Failure of resistance multiplication factor (1.05-1.50)	1.10
L_w & L_t	Line width and thickness	3µm, 0.5µm
Others	Voltage limit V_l (10V), current limit I_l (200mA), TCR (0.38%/°C)	

Output results:

Test ambient temperature; TCR; Target test temperature; failure criteria; initial resistance; resistance and stress current at convergence; time to failure; average resistance during stress; average stress current during stress;


Maintain T_0 (room)
FHpin←I_{meas}, FLpin←G
MHpin←m, MLpin←m
Delay 10ms
Measure V, R_0 =V/I
R_0< V_l/I
Y
Initial R
Calculate the TCR @ T_0
Follow the TCR measure procedure (optional)
Calculate R_{tar} at T_{tar} using TCR
Current Ramp, Force I
I_{start}, ramp rate
Measure R, Delay time 10ms
R< R_{fail},
or V_l/I
A
? (R-R_0)
>3.8 % R_0
Calculate **T←(a)**
Calculate **θ←(b)**
Force a new current I
I←(c)
Measure voltage V,R
Calculate T, θ
? T=T_{tar} ±0.5°
Y
N
N=0, n=n+1,
? n >3
N
? T-T_{tar}
within 2%
A
N=N+1
To test option
? N> 3
Y
N
Force I again
Delay time T_{delay}
A: Exit & Record Failure Data.
(a): Calculate T as a known R.
$T = T_0 + \frac{(\frac{R}{R_0}) - 1}{TCR_0}$
(b): Calculate the differential thermal resistance θ
θ=(T-T_0)/VI
(c): Calculate new stress current
$\Delta I = \sqrt{\frac{\Delta T}{\theta \cdot R}} = \sqrt{\frac{T_s - T_0}{\theta \cdot R_0[1+TCR_0(T_s - T_0)]}}$

Test Option 1 **Iso-J** (Force a constant current at this value for the rest of the test)



Test Option 2 **Iso-J** (Force a constant current at this value for the rest of the test)