Electromigration

Metallization Failure: the failure relate to the metallization of the semiconductor process.
It includes: Electromigration; contact electromigration; via electromigration; corrosion etc….

Electromigration:

Electromigration is the mass transport of metal atoms in metal line during electric conduction due to the momentum transfer between conducting electrons and diffusing metal atoms. (In another word, when high current densities are passed through the metal line, the force exerted by the flow of electrons can cause the movement of metal atoms in the direction of the electron flow.) Normally it can occur in the metal lines when current density becomes large enough. (0.5X $10^6 A/cm^2$, etc.) High temperature also promotes the process.

Causes:
As we known, electromigration is forced atomic diffusion with the driving force due to an electric field and associated electric current in metal.
Under the influence of an electric field and the subsequent flow of electric current, there exist driving force for electromigration. There are two types of forces that contribute to the driving force. One is the direct force (F_d) and the other is wind force (F_w). F_d is force on an atom due to the long-range electric field accompanying the electron transport process. F_w is arising from the interaction of a moving gas of free electrons with an atom. It results from the scattering effect of electrons on metal atoms. In most case, the wind force is dominant significantly larger in magnitude for electromigration.
There are two major types of diffusion mechanism that is responsible for electromigration. *Lattice diffusion* and *Grain Boundary Diffusion*. In most case, transport along grain boundaries usually dominates in normal operating conditions. Lattice diffusion is much slower until temperatures approaching 1/2 to 2/3 the absolute melt temperature of the material depending on the line width.

EM tests:

In order to induce or reproduce electromigration failures that would ordinarily occur under field operation stress, but within an operation time that is shorter than required to produce the same electromigration failures under field usage stresses, many highly-accelerated electromigration test techniques were conducted.
(1) SWEAT (Standard Wafer-Level Electromigration Accelerated Test)
(2) Isothermal Electromigration Test

Standard Wafer-Level Electromigration Accelerated Test (SWEAT)

Test description:

SWEAT test uses a feedback control loop to adjust the stress current applied to the test line. The stress current is adjusted so that the estimated target time to failure (MTTF) is maintained within programmed error band. The MTTF is derived from Black's equation, at the selected target value.

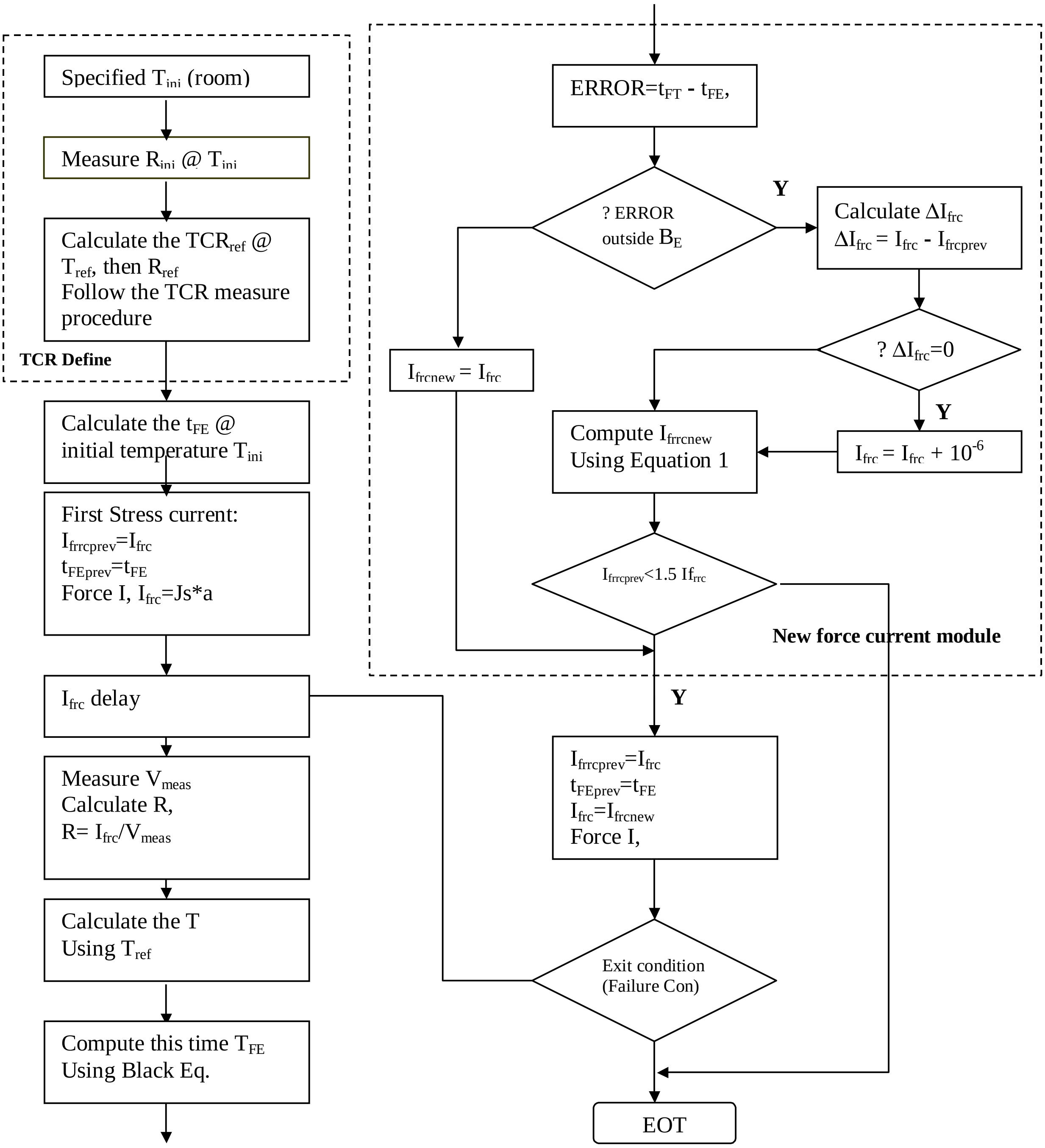
Similar to the isothermal EM test, the SWEAT test also force a stress condition in the metal line by applying a forced current, then measure the change in the line's resistance to get feedback on the temperature of the line. The SWEAT test uses this information to force a constant stress condition, with the stress being calculated using the current density and temperature terms from Black's Equation (see *Definition*), while the isothermal test uses this information to adjust the current to achieve a specified line temperature.
It rapidly force the specified stress conditions, then actively control the current to maintain this stress condition for some short period of time (typically three seconds). During this period, the thermal mass of the line and the surrounding oxide are heated to the stress temperature. Once thermal stability is reached, the current is generally fixed for the duration of the test (the JEDEC specification allows the current to be fixed, the power to be fixed, or the current to be continually adjusted, based on the feedback from the line resistance). During the test, the resistance of the line is measured. A failure condition is specified in terms of a percent change in resistance. The test continue until the failure condition is met or the test time exceeds some specified maximum stress period.
A brief account of the test method is given as follows:

Test procedure:

- The test begins with a measurement of the resistance of the metal line and the determination of its TCR at room temperature.
- This resistance and TCR measurement will be used as references throughout the test.
- A high current density typically at $10MA/cm^2$ is applied and a change in resistance is then calculated.
- Based on this change and the TCR of the metal used, a line temperature is measured, using the following equation.

  $$T = \frac{R(T)xR(T_{ref})}{R(T_{ref})xTCR(T_{ref})} + T_{ref}$$

  Where T_{ref} is the reference temperature at which the experiment started.
- Knowing the line temperature and the forced current, a "Stress Level" is calculated.
- The calculated stress level is then compared to the desired stress level.
- Based on the difference between the desired stress level and the measured stress level, a second guess as to the stress level is made and forced through the line.
- This cycle of guess and correction is performed until the intended stress condition is obtained.
- Once obtained, the current is continually adjusted until the test line reaches thermal equilibrium and is fixed for the rest of the test.
- Measurement will be continued till the targeted DUT resistance change is reached.



To "New force current module"

Definition:

(1) The estimated time to failure is from Black equation:

$$t_{FE} = \frac{A}{jn}\exp\left[\frac{E_a}{kT}\right]$$

Where A is a constant dependent on metal film material and structure,
n is the current density factor depend on various fabrication and test parameters, (usually 2.0)
E_a is the activation energy, K is Boltzmann's constant and T is temperature.

(2) Error band B_E
a boundary for the estimated t_{FE} around the target time to failure.

(3) new force current can be calculated from:

$$I_{frcnew} = I_{frc} + (t_{FT} - t_{FE})\left(\frac{I_{frc} - I_{frcprev}}{t_{FE} - t_{FEprev}}\right) \qquad (1)$$

Input parameter:

t_{FT}, (target times to failure), B_E , T_{ini}, T_{ref}, Js, a, T_{delay}, Failure condition,

Output parameter:

t_{FE} , t_f , R_f , J_f , T_f ,

The analysis:

There are two models for the life-time of the failure mechanism of EM has been described here. One is Black model. Another model is Frost and Poole.

Black Equation:

$$TTF = \frac{A}{J^n} e^{\frac{E_a}{kT}}$$

Where: *TTF* is time to fail A is a material dependent constant that is a function of line width, *J* is the current density in, *n* is the current density exponent, $E_0$is the thermal activation energy, *k* is Boltzmann's Constant, *T* is the absolute temperature.

This equation relates the rate of electromigration in a line to the steady-state, current-density stress applied to the line. However, the time to fail of the line is also affected by stress gradients in the line. Both thermal gradients and mechanical stress can cause preferential self diffusion in metal material, and have been known to cause the failure of a line without any electrical stress. The effect of the gradients either enhance the rate of electromigration or retard the rate of electromigration depending on the direction of the two effects.
Black's Equation does not include variables for stress gradients, even though these values are known to affect the lifetime of a device greatly. The SWEAT test structure is designed to produce high stress gradients, so it should not produce the same results as that measured using an ASTM standard test structure.