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SOLID-STATE RELIABILITY ASSESSMENT AND QUALIFICATION METHODOLOGIES

Introduction

Reliability is a measure of the ability of a product to continue to meet data sheet specifications over time. In any population of solid-state products there is a range in the time to failure, which is the time-to-failure distribution. Since the typical time-to-failure distribution will have a central characteristic in the order of hundreds or thousands of years, means must be derived to assess the time-to-failure distribution in real time. Failure mechanism models provide a physical and mathematical representation of how the time-to-failure distribution will change by changing the influencing factors from application conditions.

Reliability assessment and qualification systems consist of the following:

- a) a list of applicable failure modes, failure mechanisms, failure kinetics, and causes;
- b) a failure model, including as appropriate the validity and correctness of the model;
- c) a means to accelerate the failure process;
- d) defined application conditions (mission profile) to generate a list of criteria for the acceptability of the failure rates;
- e) the definitions and/or criteria for a failure, e.g., when is a deviation a failure.

Reliability assessment systems provide economic benefit for both manufacturers and users. Manufacturers can quantify the reliability of their products in order to understand warranty and other costs associated with potential reliability failures. Users can estimate the reliability of systems using solid-state products in order to quantify costs associated with system operation or failures.

Reliability assessment systems consist of a suite of accelerated stresses and the associated sample plans used for monitoring or acceptance. The statistics used to determine the sample plans are not covered herein. Note: the sample plans should be based on the purpose of the sampling, e.g., monitoring or qualification, the expected failure rate, and the expected application requirements. References such as *Sampling Inspection Tables Single and Double Sampling* by Harold F. Dodge and Harry G. Romig; *Some Theory of Sampling* by William Edwards Deming; *Statistical Method from the Viewpoint of Quality Control* by Walter A. Shewhart; *Guide to Quality Control* by Kaoru Ishikawa, and *A Sampler on Sampling* by Bill Williams provide both the theoretical background and practical applied approaches for choosing appropriate sample plans.

Accelerated stress methods are usually categorized by the location of the failure mechanisms they are expected to stimulate. The stress methods are normally classified as die-related, package-material-related, or packaged-product-related, including the interconnection of die and package. Eventually there may be an additional category and section within this publication for stress methods associated with the failure mechanisms of the interface between either the package and the socket or the package and the printed circuit board (PCB). This publication pertains primarily to integrated circuits; however, that does not prohibit adding additional categories and sections for stress methods that include system-level failure mechanisms. Stress methods are also categorized by the cause of failure, e.g., process variance, defects, or wearout. The stress factor, e.g., temperature, electric field, humidity, mechanical stress, voltage, or current density, may also be used for categorization.

While reliability modeling has been around for more than a century, for integrated circuits the seminal paper "Reliability in the Bell System" published in *Proceedings of the IEEE*, February 1974 by Peck & Ziert clarified the concepts of temperature acceleration and failure rate modeling. The following quote is pertinent: "The reaction rate will be related to failure time through some undefined function but,

Introduction (cont'd)

Regardless of that function, the failure time should follow the temperature dependence of the Arrhenius equation.

It must be remembered, however, that the apparent activation energy of the process of reaching some defined end-point limit of a parameter, as measured by the effect of temperature on the failure distribution, is not necessarily the same as the activation energy of the process itself by which the parameter changes.”

The reaction rate for a given temperature-activated failure mechanism may be calculated from the equation:

$$R = R_0 \exp(-E_a/kT)$$

where

R is the reaction rate;
 R_0 is a constant;
 E_a is the activation energy (eV);
 k is Boltzmann's constant (8.62×10^{-5} eV/K);
 T is the temperature (K)

Since we are looking for the changes in the failure time (i.e., the probability-density function of time-to-failure), we use the common equation for the temperature acceleration factor:

$$A_T = \lambda_{T1}/\lambda_{T2} = \exp[(-E_{aa}/k)(1/T_1 - 1/T_2)]$$

where

A_T is the acceleration factor due to changes in temperature;
 λ_{T1} is the observed failure rate at test temperature T_1 (h^{-1});
 λ_{T2} is the observed failure rate at test temperature T_2 (h^{-1});
 E_{aa} is the apparent activation energy (eV);
 k is Boltzmann's constant (8.62×10^{-5} eV/K);
 T_1 is the temperature of test 1 (K);
 T_2 is the temperature of test 2 (K)

The temperature acceleration factor is derived from the Arrhenius equation for failure rate, and may be calculated from the equation:

$$\lambda_T = \lambda_0 \exp(-E_{aa}/kT)$$

where

λ_T is the failure rate at temperature T ;
 λ_0 is the base failure rate (h^{-1});
 E_{aa} is the apparent activation energy (eV);
 k is Boltzmann's constant (8.62×10^{-5} eV/K);
 T is some temperature (K)

NOTE The Arrhenius relationship is for temperature accelerated failure mechanisms, whether the failure rate increases or decreases with temperature. Some failure mechanisms have stronger dependencies on other factors (e.g., voltage, humidity) so the Arrhenius relationship may not be applicable.

Introduction (cont'd)

Various population failure distributions, called *probability density functions* (PDF) and *cumulative distribution functions* (CDF), are mathematical models of failure rates. These distributions are specifically the *cumulative distribution function of the time-to-failure* (*cumulative mortality function*), *cumulative hazard function*, *cumulative reliability function*, *instantaneous failure rate*, or *probability density function of time-to-failure* (*mortality function*) depending on what failure rate is intended to be modeled and described.

The simplest way of visualizing reliability as a function of time is a graph. The most common graph is the *bathtub curve* showing the areas of *infant mortality*, *useful life*, and *wearout*. The reliability is quantified in units of *FITs*, *MTTF* (Mean-Time-To-Failure), or *MTBF* (Mean-Time-Between-Failures).

Failure rates are experimentally determined by stressing devices. The *observed failure rate* from stress is converted to the *quoted failure rate* predicted for field applications using an *acceleration factor* calculated using the *Arrhenius Equation for reliability* and an *apparent activation energy* estimated from reliability stress results at different conditions. While the *Arrhenius Equation for reliability* is most often used to model temperature acceleration of the failure rate distribution, the equation can be used for other stress factors, e.g., voltage, humidity.

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SOLID-STATE RELIABILITY ASSESSMENT AND QUALIFICATION METHODOLOGIES

(From JEDEC Board Ballot JCB-18-38, formulated under the cognizance of the JC-14.3 Subcommittee on Silicon Devices Reliability Qualification and Monitoring.)

1 Scope

This publication applies to all integrated circuits and their associated packages. The document summarizes the suite of reliability documents and publications available. These documents address reliability qualification, reliability stress testing, and reliability modeling.

The purpose of this publication is to provide an overview of some of the most commonly used systems and test methods historically performed by manufacturers to assess and qualify the reliability of solid-state products. The appropriate references to existing and proposed JEDEC or joint standards and publications are cited. This document is also intended to provide an educational background and overview of some of the technical and economic factors associated with assessing and qualifying microcircuit reliability.

2 Terms and definitions

The following terms and definitions are fundamental in the field of reliability. Virtually all of the terms have been defined before but some were merely used without definition in one or more of the publications listed in clause 9. Some terms and/or definitions have been revised technically and/or grammatically and are not the same as currently exist in other publications. The updating of publications, including JESD88, JEDEC Dictionary of Terms for Solid State Technology, is ongoing. The intention is that the other publications will be aligned with the terms and definitions presented herein as those publications are revised. Terms and definitions associated with failure mechanisms and reliability models can be found in JEP122.

If not otherwise noted, in general for the below definitions, when one sees “time” or “time-to-failure”, the definitions also apply for “cycles” or “cycles-to-failure”, or other measure of the duration measurement required for failure. Repeating the alternate terms is not necessary to convey understanding.

acceleration factor (A, AF): For a given failure mechanism, the ratio of the time it takes for a certain fraction of the population to fail, following application of one stress or use condition, to the corresponding time at a more severe stress or use condition.

NOTE 1 Times are generally derived from modeled time-to-failure distributions (lognormal, Weibull, exponential, etc.).

NOTE 2 Acceleration factors can be calculated for temperature, electrical, mechanical, environmental, or other stresses that can affect the reliability of a device.

NOTE 3 Acceleration factors are a function of one or more of the basic stresses that can cause one or more failure mechanisms. For example, a plot of the natural log of the time-to-failure for a cumulative constant percentage failed (e.g., 50%) at multiple stress temperatures as a function of $1/kT$, the reciprocal of the product of Boltzmann’s constant in electronvolts per kelvin and the absolute temperature in kelvins, is linear if one and only one failure mechanism is involved. The best-fit linear slope is equal to the apparent activation energy in electronvolts.

NOTE 4 The abbreviation AF is often used in place of the symbol A.

2 Terms and definitions (cont'd)

acceleration factor, stress (A_s): The acceleration factor due to the presence of some stress (e.g., current density, electric field, humidity, temperature cycling).

acceleration factor, temperature (A_T): The acceleration factor due to changes in temperature.

NOTE 1 This is the acceleration factor most often referenced. The Arrhenius equation for reliability is commonly used to calculate the acceleration factor that applies to the acceleration of time-to-failure distributions for microcircuits and other semiconductor devices:

$$A_T = \lambda_{T1}/\lambda_{T2} = \exp[(-E_{aa}/k)(1/T_1 - 1/T_2)]$$

where

E_{aa} is the apparent activation energy (eV);
 k is Boltzmann's constant (8.62×10^{-5} eV/K);
 T_1 is the absolute temperature of test 1 (K);
 T_2 is the absolute temperature of test 2 (K);
 λ_{T1} is the observed failure rate at test temperature T_1 (h^{-1});
 λ_{T2} is the observed failure rate at test temperature T_2 (h^{-1}).

NOTE 2 The best-fit linear slope of a plot of the natural log of the time-to-failure as a function of $1/kT$, the reciprocal of the product of Boltzmann's constant in electronvolts per kelvin and the absolute temperature in kelvins, is equal to the apparent activation energy in electronvolts.

NOTE 3 $\lambda_q = \lambda_o \cdot A_T$, where λ_q is the quoted (predicted) system failure rate at some system temperature T_s , λ_o is the observed failure rate at some test temperature T_t , and A_T is the temperature acceleration factor from T_t to T_s .

acceleration factor, voltage (A_V): The acceleration factor due to changes in voltage.

acceleration model: A mathematical formulation of the relationship between (1) the rate (speed) of a degradation mechanism or the time-to-failure and (2) the conditions or stresses that caused the degradation.

activation energy (E_a): The excess free energy over the ground state that must be acquired by an atomic or molecular system in order that a particular process can occur.

NOTE The activation energy is used in the Arrhenius equation for the thermal acceleration of physical reactions. The term "activation energy" is not applicable when describing thermal acceleration of time-to-failure distributions, e.g., in the Arrhenius equation for reliability, hence the need for the term "apparent activation energy".

apparent activation energy (E_{aa}): An energy value, analogous to activation energy, that can be inserted in the Arrhenius equation for reliability to calculate an acceleration factor applicable to changes with temperature of time-to-failure distributions.

NOTE 1 An apparent activation energy should be associated with a specific failure mechanism and an observed time-to-failure distribution to calculate the acceleration factor for converting the observed failure rate to the quoted failure rate at a different temperature.

NOTE 2 An activation energy is a measure of the heat energy needed to establish the rate of reaction for a specific failure mechanism. The reaction rate and other contributing factors, e.g., radiation, voltage, humidity, magnetic fields, determine the unique time-to-failure distribution for the modeled failure mechanism.

NOTE 3 The apparent activation energy is empirically determined from the change in an observed time-to-failure distribution with temperature.

2 Terms and definitions (cont'd)

Arrhenius equation (for reliability): An equation used to calculate thermal acceleration factors for semiconductor device time-to-failure distributions:

$$A_T = \lambda_{T1}/\lambda_{T2} = \exp [(-E_{aa}/k) (1/T_1 - 1/T_2)]$$

where

A_T is the acceleration factor due to changes in temperature;

λ_{T1} is the observed failure rate at test temperature T_1 (h^{-1});

λ_{T2} is the observed failure rate at test temperature T_2 (h^{-1});

E_{aa} is the apparent activation energy (eV);

k is Boltzmann's constant (8.62×10^{-5} eV/K);

T_1 is the absolute temperature of test 1 (K);

T_2 is the absolute temperature of test 2 (K).

NOTE 1 The original Arrhenius equation (for atomic or molecular processes and chemical reactions) used the gas constant, not an activation energy, in the exponent. The “Arrhenius equation (for reliability)”, used to calculate a thermal acceleration factor for a given observed time-to-failure distribution and E_{aa} , is in the form of the quotient of two Arrhenius equations, so that the acceleration factor from one temperature to another can be calculated.

NOTE 2 $\lambda_q = \lambda_o \cdot A_T$, where λ_q is the quoted (predicted) system failure rate at some system temperature T_s , λ_o is the observed failure rate at some test temperature T_t , and A_T is the temperature acceleration factor from T_t to T_s .

bathhtub curve: A plot of failure rate versus time or cycles that exhibits three phases of life: infant mortality (decreasing failure rate), intrinsic or useful life (relatively constant failure rate), and wearout (increasing failure rate).

Boltzmann's constant (k): A constant equal to 1.38×10^{-23} joule per kelvin or 8.62×10^{-5} electronvolts per kelvin.

cumulative distribution function of the time-to-failure; cumulative mortality function [F(t)]: The probability that a device will have failed by a specified time t_1 , or the fraction of units that have failed by that time.

NOTE 1 The value of this function is given by the integral of $f(t)$ from $t = 0$ to $t = t_1$ and is generally expressed in percent (%) or in parts per million (ppm) for a defined early-life failure period. See “probability density function of the time-to-failure” for $f(t)$.

NOTE 2 The abbreviation CDF is often used; however, the symbol $F(t)$ is preferred.

cumulative fraction failing (CFF): The total fraction failing based on the starting sample size over a given time interval.

NOTE This value is generally expressed in percent (%) or in parts per million (ppm).

cumulative hazard function [H(t)]: The fraction of units that have failed referenced to the survivors (not to the initial number of units).

NOTE The value of this function at a specified time t_1 is given by the integral of $h(t)$ from $t = 0$ to $t = t_1$. See “instantaneous failure rate; hazard rate” for $h(t)$.

cumulative reliability function [R(t)]: The probability that a device will still be functional at a specified time t_1 , or the fraction of units surviving to that time.

NOTE $R(t) = 1 - F(t)$. See “cumulative distribution function of the time-to-failure” for $F(t)$.

defect, (physical): A physical anomaly that adversely affects function or performance.

2 Terms and definitions (cont'd)

degradation defect: A physical defect created by the natural changes in the properties of materials over time that is manifested after some period of operation.

early life: The period of initial use by the customer.

NOTE This period typically ranges from three months to one year of operation.

early-life-failure rate (ELFR): The failure rate that may occur during the period of initial use by the customer.

early-life-failure (ELF) test: An accelerated test designed to measure the early-life-failure rate (ELFR).

NOTE The calculation procedure is specified in JESD74, sample sizes are noted in JESD47, and stress methods are identified in JESD22-A108 and other documents in the JESD22 series.

early-life period (t_{ELF}): The specified early-life period as defined by the user or the supplier.

electrostatic discharge (ESD): A sudden transfer of electrostatic charge between bodies or surfaces at different electrostatic potentials.

failure: (1) The loss of the ability of a device to meet the electrical or physical performance specification that (by design or testing) it was intended to meet.

(2) A device that has failed.

(3) The lack of the ability of a device to meet the electrical or physical performance specifications that (by design or testing) it was intended to meet.

failure cause: The physical process that created the failure mechanism.

NOTE See note 3 to “failure mode”

failure kinetics: The characteristics of failure for a given physical failure mechanism, including (where applicable) acceleration factor, derating curve, activation energy, median life, standard deviation, characteristic life, instantaneous failure rate, etc.

failure mechanism: The physical, chemical, electrical, or other process that has led to a nonconformance.

NOTE A failure mechanism may be characterized by how a degradation process proceeds including the driving force, e.g., oxidation, diffusion, electric field, current density. When the driving force is known, a mechanism may be described by an explicit failure rate model; identifying that model with associated parameters is the main objective of this document.

NOTE 2 See note 3 to “failure mode”

failure mode: The way in which a failure mechanism manifests itself in a failing component.

NOTE 1 Examples of failure modes are a visual blemish, a bent lead, a foreign particle or material, an incorrect dopant profile or grain size, a scratch, an electrical fault (open, short, leakage, inadequate slew rate or noise margin, stuck at high or low, etc.).

NOTE 2 Failure rate distributions for a given failure mode can be modeled only when the failure mechanism and the relevant independent variables (forcing functions) are known.

NOTE 3 The relationship among the four terms is illustrated by the following: if the *failure mode* is input leakage, the *failure mechanism* is oxide rupture, the *failure cause* is ongoing application of a voltage field across an oxide containing an interstitial dislocation, and the *root cause* is a contaminant in the oxide growth furnace.