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**RELIABILITY QUALIFICATION OF SEMICONDUCTOR DEVICES
BASED ON PHYSICS OF FAILURE AND RISK AND OPPORTUNITY ASSESSMENT**

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Introduction

The penetration of semiconductor products into an increasing variety of application segments together with the economic forces of cost and time-to-market require efficient qualification concepts. This requirement influences the organization of the qualification process in conjunction with the development / innovation process as well as the qualification methodology. Proactive practices such as advance quality planning, "incremental qualification" and confirmation during development have to be practiced in order to meet time to market goals. Results of these activities including the use of further available knowledge will be the basis for the qualification as evidence for the readiness of the product for the market.

These aspects are considered here by a straightforward approach to qualification being part and result of careful development work.

Semiconductor devices specialize to application segments

The different application segments drive the increase and specialization of functionality, and also require optimum solutions for economic integration of components into their systems, their application conditions and application times. This is achieved by

- specific technological adaptation of the product construction (chip internal construction, package or module design) frequently associated with new materials and new or modified technologies;
- use of products of mature designs and technologies by extending the knowledge about their applicability in more demanding applications.

Time-to-market requires efficient quality planning and confirmation

Shortening time to-market period forces one to consider

- integration of qualification into the innovation process with early start of the qualification activities replacing qualification as a separate and sequential activity,
- effective use of knowledge, i.e., applying existing results for qualification,
- compatibility with simultaneous engineering practices.

Reliability qualification will refer to physics-of-failure knowledge

As a consequence, the practices of qualifying products for reliability are changing

- from reactive activities at the end of a development cycle applying uniform and predefined stress testing with generic qualification plans
- to measures deliberately integrated into the development cycle making proactive use of stricter physics-of-failure based testing with respect to the product construction and the use conditions of the application segment
- to approaches to measure the robustness with respect to well specified application conditions.

The approach taken is to:

- apply a systematic procedure which enables concentration on those product properties with respect to product construction and application conditions which really need to be qualified (part I),
- arrange the qualification methodology to correspond to the relationships between designs; technology, manufacturing and product life phases at use conditions (part II).

RELIABILITY QUALIFICATION OF SEMICONDUCTOR DEVICES BASED ON PHYSICS OF FAILURE AND RISK AND OPPORTUNITY ASSESSMENT

(From JEDEC Board Ballot JCB-08-63, and JCB-13-58, formulated under the cognizance of the JC-14.3 Subcommittee on Silicon Devices Reliability Qualification and Monitoring.)

1 Scope

The purpose of this procedure provides a consistent frame work for reliability qualification using the Physics-of-Failure (PoF) concept, which

- is flexible with respect to the requirements of the intended application and market,
- makes optimum use of the supplier's advance quality planning and demonstration results gained during design and development and applicable knowledge based on design and technology similarities.

Planning quality and reliability in advance and gaining reliability results with the progress of a design and development process is efficiently supported by a systematic procedure for risk and opportunity assessment.

The qualification concept is based on customer - supplier partnership in order to achieve optimized efforts. The methodology applies to the reliability qualification of semiconductor devices and the processes for their development and manufacturing.

2 References (informative)

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[9] R. Blish, N. Durrant, *Semiconductor Device Reliability Failure Models*, Sematech RTAB, 5/2000, <http://www.semtech.org/public/docubase/abstracts/3813axfr.htm>.

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[12] H. Keller and A. Preussger, "Robustness Validation", Tutorial ESREF 2006

2 References (informative) (cont'd)

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[14] Robustness Validation Manual, ZVEI 2010

3 Terms and definitions

For the purpose of this publication, the following terms and definitions apply.

acceleration model: A mathematical formulation of the relationship of rate (speed) of a degradation mechanism or time-to-failure to stresses or use conditions.

application requirements for quality and reliability: The quality and reliability properties of the product required for the intended specified use conditions.

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

defect density: The number of defects on a chip divided by its area.

design rules: The basic rules and regulations for circuit design with electrical and geometrical parameters specified for the range of application conditions and time.

mission profile: The simplified representation of all of the relevant conditions to which a device will be exposed in its intended application throughout the full life cycle.

physics-of-failure (PoF) concept: An approach to the design and development of reliable product to prevent failure, based on the knowledge of root cause failure mechanisms.

NOTE The PoF concept is based on the understanding of

- the relationships between requirements and the physical characteristics of the product and their variation in the manufacturing processes, and
- the reaction of product elements and materials to loads (stressors) and interaction under loads and their influence on the fitness for use with respect to the use conditions and time.

qualification: The process of demonstrating that an entity is capable of meeting or exceeding the specified requirements.

qualification requirements: The quality and reliability properties of the product suited to demonstrate compliance to the application requirements.

reliability qualification: The process of demonstrating that an entity is capable of meeting or exceeding the specified reliability requirements, usually by tests using accelerating conditions and proven models.

robustness: The capability of functioning correctly or not failing under varying application and production conditions.

risk and opportunity assessment process: The systematic procedure intended to; 1) proactively avoid problems such as unfulfilled requirements, demands, and expectations, 2) take advantage of capabilities (opportunities) that may exceed the requirements for a given approach, and 3) initiate appropriate measures to exploit opportunities and avoid, reduce, or prevent risks that would influence the user.

3 Terms and definitions (cont'd)

Safe Operating Area (SOA): The parameter space which guarantees functionality within specification.

service life: the total lifetime of a system.

useful life (of an unrepairable unit): The time interval between the start of use of an unrepairable unit and its statistically expected failure in an application.

validation: The process of confirming the verification process under use conditions.

verification: The process of confirming that the specified requirements are fulfilled, excluding reliability requirements.

wafer level reliability (WLR): The characterization of product or technology reliability on wafer level by applying stress to specific test structures.

4 Planning for quality and qualification: situation, approach and procedure

4.1 Application requirements

The requirements of the customer or the application segments in general refer to:

- application conditions and time (use mission profile, service life),
- processing conditions at the equipment manufacturer,
- storage and transportation conditions,
- expected statistical reliability properties, e.g., tolerable early failure rate and period.

The different application segments vary concerning their system requirements, application conditions and planned time of use ranging from benign environments and short-term use to harsh environmental conditions and long-term application. This is represented e.g., by chip cards, mobile phones, consumer electronics, computers, automotive applications, telecom networks, each with individual use or mission profiles.

Requirements are specified in terms of:

- robustness against external loads
- expected statistical reliability properties, e.g., tolerable early failure rate and period.

4.2 Qualification concepts

Qualification of products means to confirm their fitness for use as a result of appropriate processes for their realization. This includes:

- verification of their function and performance,
- validation in the system application (less for commodities),
- qualification for processability (OEM board assembly) and reliability.

4.2 Qualification concepts (cont'd)

There are two different approaches to the part qualification for processability and reliability:

- a) examination of the product as a "black box" by comparing its properties to specified requirements as "final inspection" after product development at the manufacturer (or "incoming inspection" at the user). It is, in this sense, reactive,
 - it adds, in general, an additional phase to development, and it hardly differentiates in giving focus on those issues which really need to be qualified,
 - it applies for reliability the "stress test driven qualification", which confirms a stress test capability by which "a certain level of quality/reliability" can be expected in the application. The intention of this traditional method is to test for the existence of failure modes, which have been observed in application, by stress tests at elevated conditions. This means, it is mainly based on experience with products of matured technologies. The variable parameters of test and stress conditions are restricted to those, which can be set and varied from outside of the products. These are mainly electrical operational conditions within data sheet limits and environmental conditions. Also the control of the resulting internal stresses is limited or not feasible. The evaluation is essentially qualitative, as the relations between applied stress test conditions and lifetime at use conditions to be covered by tests are usually not established. Therefore the meaningfulness of results is questionable in case of new or changed materials or technologies.
- b) conclusive derivation of qualification targets and activities from application requirements and planned product construction in a proactive way as described in failure mechanism specific knowledge based qualification [11, 12, 13, and 14]:
 - it considers qualification as an integral part of design and development with early involvement in this process, i.e., starting in the definition phase and agreeing to requirements and checking their feasibility;
 - it makes extensive use of applicable results, e.g., by considering the technological and design properties common to all products or product elements of a technology (family) or results gained on similar products;
 - it adjusts the qualification to the application conditions and the time period of the intended application on a quantitative level with knowledge of active stresses and potential failure mechanisms based upon the "Physics-of-Failure Concept".

4.3 The Physics-of-Failure concept

The Physics-of-Failure (PoF) concept is an approach to design and development of reliable product to prevent failure based on the knowledge of root cause failure processes [1, 2, 3]. It is based on understanding

- the relationships between requirements and the physical characteristics of the product (and their variation in the production process),
- the interactions of product materials with loads (stresses at application conditions) and their influence on product reliability with respect to the use conditions.

Reliability results from adequate stability of product properties at the intended conditions of use and time. Products may change with time by physical mechanisms as reaction of materials to loads and as material interactions influenced by loads occurring in use. Materials, their interactions, and the stresses acting on them principally determine potentially active mechanisms.

4.3 The Physics-of-Failure concept (cont'd)

The PoF-concept considers the potential failure mechanisms individually. Their investigation provides the different stress-time-relationships, known as reliability models. Application of these models (and developing them where necessary) enables one to design and qualify a product for the intended application. In detail this has to be done on the level of individual product elements, as their design determines materials, imposed stresses and related mechanisms. More details of this approach to reliability qualification are outlined in clause 5.

4.4 The systematic procedure: the Risk & Opportunity Assessment Process

Developing and qualifying a product (and its technology) successfully requires understanding how product performance and reliability (as a result of construction/design, process, materials) relate to use requirements (functional properties and application conditions).

The basic approach of identifying design and qualification aspects is to compare the requirements for the product to the presently available abilities of fulfilling them, see Figure 1. The differences that will be found are gaps requiring solutions or opportunities that can be exploited. Appropriate measures to be taken depend on the level of opportunities or of risks associated with gaps.

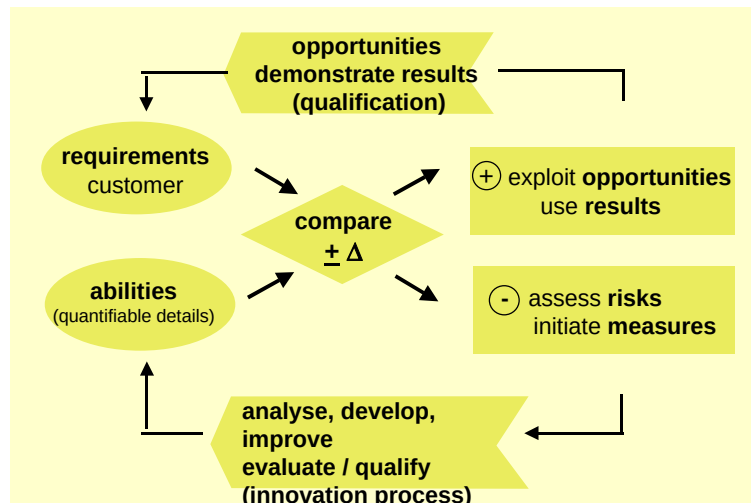


Figure1 — Principle of comparing requirements to abilities and taking appropriate actions

It is a systematic process including a deductive approach looking at the transformation of requirements by product and process properties (view from outside to inside) and an inductive approach looking at potential faults in the product and processes and their effects for the use of the product (view inside to outside) with the following consecutive steps (for details see Table 2):

- 1) collection of requirements and expectations as inputs,
- 2) identification of product/process elements which have influence on meeting the requirements,
- 3) definition of their appropriate target values to satisfy function and reliability requirements,
- 4) checking for potential faults and their effects (inductive approach),
- 5) stating the actual ability to realize them for function and reliability,
- 6) evaluation of the risks/opportunities,
- 7) definition of required actions to exploit opportunities respectively to avoid or control risks, including the background information or references to them.

4.4 The systematic procedure: the Risk & Opportunity Assessment Process (cont'd)

4.4.1 Product tree analysis

The systematic procedure for step 1) and 2) requires an ordering scheme, which enables one to see in detail, how requirements can be fulfilled by individual product properties. One approach that may be used to do this is the Product Tree Analysis (PTA). It represents the structure of the product decomposed into its elements, where each element is the result of a process step or section, see Figure 2a, and also for checking the propagation of potential faults at process steps and product elements (inductive approach, Figure 2b into the product application. Thus, it also allows one to trace properties of an element to the relevant process step at a measurable level.

As an example: A semiconductor component would be separated into the package parts and the chip, each with the associated process sections. This procedure can be continued to further levels of detail, e.g., going into wafer manufacturing, provision of masks, design process, etc. The PTA also may serve for structuring of work packages for different specialist groups (chip design, package design, etc.).

4.4.2 Target values

In principle, the functional requirements propagate from the requirements for the complete product down to the elements and process steps of the PTA in a hierarchical manner (step 3 of process). This serves as the basis for answering questions like:

- Which element or which property is “responsible” for the fulfillment of a specific functional requirement?
- Which target values and acceptable tolerances of the influencing element characteristic(s) and / or process are needed to meet the requirement?

This is answered using physical relationships between the influencing elements parameters and a requirement. Thus, if the target can be achieved, then the requirement will be achieved, Figure 3a. Interactions between elements will show up, when different elements have an impact on the same requirement or one element has an impact on various requirements.

For reliability and processability, the requirements are the conditions of operation and time in application respectively, and the processing conditions at the equipment manufacturer (OEM). Corresponding questions are (step 4 of process):

- Which kind of stress (load) acts during operation at an element and which mechanisms may stimulate degradation of an element property?
- Which stress intensity drives the degrading mechanism?
- What level of degradation results in a failure (failure criterion)?
- What is the resulting useful life period?

Here, the physics based reliability models apply, which describe the relationship between the target of acceptable stress intensity and the planned application time. Figure 2B gives an example how a parameter P degrades over time for three different stress intensities starting with $P_{\text{target}}=P(0)$. The lifetime ends when P_{limit} is reached.