RELIABILITY & QUALIFICATION OF ADVANCED MICROELECTRONICS FOR SPACE APPLICATIONS

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Abstract - New spacecraft designs require highly advanced state-of-the-art microelectronic devices and structures developed and fabricated at research and development laboratories for a specific application and in small quantities. It is critical that a cost effective and efficient reliability and qualification approach is used to determine the suitability of the technology in question to the intended application. However, the nature of the developments at research and development laboratories and the limited production volume makes this a difficult issue to address. This paper provides a discussion of the subject and an approach to establish a reliability and qualification methodology to facilitate the utilization of state-of-the-art advanced microelectronic devices and structures in high reliability applications.

I. INTRODUCTION

For critical space applications where the success or failure of a mission may hinge on the lifetime and performance of a single device; it is critical that all aspects of the reliability and the various known failure modes and mechanisms be addressed prior to the insertion of the component in the application [1].

The selection and application of microelectronic components in high reliability space systems requires knowledge of the component design, fabrication process, and applicable tests. In addition, reliability analysis and detailed knowledge of the application environment is necessary in order to determine the suitability of the selected component for the application. These issues are of particular importance for the application of microelectronic devices developed under R&D efforts or in small-scale production due to minimal understanding of the limitations of these devices under electrical or environmental stresses.

The high reliability user of microelectronic devices developed as an R&D effort must gain an understanding of not only the technology performance capabilities but also of the limitations of the technology and must employ methods to utilize it in a reliable fashion. The user must also understand that new failure mechanisms, not previously encountered in standard high volume production, could impact the reliability of new designs and materials. These new failure mechanisms may be a result of issues relating to process control, design limitations or material properties. In addition, many of the traditional assumptions for mean-time failure rate predictions do not hold for those new devices. Thus, new statistically meaningful qualification methods and techniques must be utilized in order to determine suitability for the intended application.

II. RELIABILITY PREDICTION

The quantitative determination of device reliability involves probability statistics, time, and a definition of failure. Given a failure criterion, the most direct way to determine reliability is to submit a large number of samples to actual use conditions and monitor their performance against the failure criteria over time. Since most applications require device lifetimes of many years, this approach is not practical. To acquire device reliability data in a reasonable amount of time, an accelerated life test at either high temperature or other acceleration factor is used. In general, the high temperature condition is used based on the observation that most failure mechanisms are thermally activated. By exposing the devices to elevated temperatures, it is possible to reduce the time to failure of a component, thereby enabling data to be obtained in a shorter time than would otherwise be required. Such a technique is known as "accelerated testing" and is widely used throughout the semiconductor industry. The rate at which many chemical processes take place is governed by the Arrhenius equation:

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

where

R = rate of the process
A = a proportional multiplier
E_a = activation energy, a constant
k = Boltzmann's constant, 8.6×10^{-5} (eV/K)
T = Absolute temperature in Kelvin

This equation has been adopted by the semiconductor industry as a guideline by which the operation of devices under varying temperature conditions can be monitored. Experimental data obtained from life tests at elevated temperatures are processed via the Arrhenius equation to obtain a model of device behavior at normal operating temperatures. Rearranging the Arrhenius equation allows the temperature dependence of component failure to be modeled as follows:

$$\ln t_2/t_1 = E_a/k\,(1/T_2 - 1/T_1)$$

where

$t_{1,2}$ = time to failure
E_a = activation energy in electron volts
T = absolute temperature in Kelvin

III. QUALIFICATION

Qualification can be defined as the verification that a particular component's design, fabrication, workmanship, and application are suitable and adequate to assure the operation and survivability under the required environmental and performance conditions.

Traditional qualification methods require extensive test and characterization of the specific component using a predetermined set of tests and characterization conditions. This approach can be very costly in schedule and expense but can result in meaningful qualification and reliability data for the specific application.

A methodology for qualification of research and development products based on detailed understanding of process dependencies and statistically meaningful reliability data is necessary. In general, the methodology is divided into three main categories; Process Qualification, Product Qualification, and Product Acceptance. The first two categories are essential for a low volume "captive" production line. The last category is a critical step used to distinguish the various application specific requirements.

Process Qualification: is a set of procedures the production facility follows to demonstrate the control of the entire process of design and fabrication using a specific technology. It addresses all aspects of the process including the acceptance of starting materials, documentation of procedures, implementation of handling procedures and the establishment of lifetime and failure data for devices fabricated using the process. Since the goal of process qualification is to provide assurance that a particular process is under control and known to produce reliable parts, it is typically performed only once in industry, although routine monitoring of the production line is standard. However, for a research and development facility, with a number of users and set-up conditions, it may be necessary on more frequent basis. In addition, any significant changes in the process may require re-qualification of the process. It is critical to remember that only the process and basic circuit components are being qualified. No reliability information is obtained for particular component designs.

Although process qualification is intended to qualify a defined fabrication procedure and device family, it must be understood that the technology is constantly evolving, and this technology evolution requires the continual change of fabrication procedures. Thus, strict application of the commonly used phrase, "freezing the production process," does not apply.

The classic process qualification also involves a series of tests designed to characterize the technology being qualified. This includes the electrical as well as the reliability characteristics of components fabricated on the line. Some of these tests are performed at wafer level and include the characterization of Process Monitors (PM), and Technology Characterization Vehicles (TCV). However, a modified approach is necessary for research and development products and fabrication methods.

Product Qualification: is the verification that a component will satisfy the design and application requirements under the specified conditions. The information sought-after in this approach is design specific and applies to devices fabricated on qualified process lines. This qualification step is composed of Design Verification and Product Characterization.

Verification of custom designs is one of the best ways of reducing engineering costs and improving reliability. Design reviews with the participation of the device manufacturer and the device user are a means of accomplishing this verification of a model or simulation and layout of the design prior to fabrication. Verification of circuit design is only applicable to custom designs and requires detailed knowledge of the design tools, device physics, layout tools, fabrication and test which requires the participation of personnel from the various disciplines.

Product characterization is another important aspect of product qualification. Thermal analysis and tests to determine the thermal characteristics of the design, along with ESD sensitivity tests, voltage ramp tests, and temperature ramp tests are all essential in obtaining an understanding of the limitations and characteristics of the design. These characterizations are applicable to both custom and standard designs and are an accepted practice for establishing product qualification. The conditions of the established characterization criteria is essential in addressing the use conditions and any anticipated worst case conditions. In addition, it is an area which allows for a more detailed understanding of the tolerances of the design and process.

Product Acceptance: Although devices may be designed by highly qualified personnel, fabricated on a process qualified production line, and verified through measurements to meet the design goals; parts with poor reliability characteristics still may exist. This may be due to variations in the fabrication process, or material flaws that were undetected, or, as is more often the case, to the device package and stress imposed on the device during packaging. Regardless of the cause, these weak devices must be found and removed before they are integrated into the system. Therefore, manufacturers of high reliability systems require the devices to pass a series of product acceptance screens, whose sole purpose is to increase the confidence in the reliability of the devices.

The level of testing performed under product acceptance is a function of the form of the deliverable. For example, the first level of acceptance testing, called "wafer acceptance test" is performed at the wafer level to assure the uniformity and reliability of the fabrication process through a wafer-to-wafer comparison. "Lot acceptance test for die" is a second level of testing that provides further reliability information, but only on a sample of the devices because of the difficulty in performing full characterization on non-packaged devices. "Packaged device screen" is performed on 100% of the devices if the deliverable is a packaged product. This level of testing should reflect the intended application conditions and also take into account the information gained in the product characterization step.

For a substantial number of research and development products, test and characterization of devices in their final packaged form is the main option to empirically assess the suitability of the product to the intended application. The challenge resides in the applied test conditions and interpretation of the resultant data. Here, knowledge of the device design, construction and fabrication process becomes critical to the actual conditions utilized during test. For screening tests, one must design the tests with the objective of detecting failure mechanisms affecting infant mortality under normal operating conditions. Consideration must be given to the bias conditions during test versus those during operation. In addition, thermal and mechanical test conditions must also be considered to reflect those used during normal operation. A pre-defined failure criteria and test parameters are a must prior to initiation of the screens.

Standard practices at JPL require devices to successfully satisfy a screening test and a detailed regiment of characterization tests prior to utilization in the final design [2]. This approach is designed with consideration for the component's design limits and the actual application conditions and environment. For research and development products with limited operating conditions and sensitive materials, special consideration must be given to thermal limits and burn-in conditions in order to maintain the integrity of the components in question .

Construction analysis and destructive physical analysis are typically utilized to help the user in understanding the construction and workmanship of the components in question. A number of user organizations tend to utilize this step very early in the selection cycle in order to provide insight into the suitability of the component for the application prior to initiation of any tests.

Special Environments: For most space applications, the user must consider how the selected component will operate under the expected environment. Fortunately, research and development products are typically designed with "special" environments in mind. However, special consideration and characterization may be necessary to determine the suitability of the product for the intended space application. Three main environmental conditions must be considered; the radiation environment, the thermal environment, and the mechanical shock environment.

The mechanical shock environment relates primarily to the shock experienced during launch. Both analytical and experimental techniques can be utilized to determine suitability of the component to the expected launch environment.

For some space applications, it may be necessary to operate devices at thermal conditions beyond those experienced in normal operation on earth. For example; operation conditions on the surface of Mars may require the devices to operate in a cyclical mode at temperatures as low as –140 °C and as high as +40 °C. This environment may present a very difficult challenge to product designed and fabricated at research and development facilities, especially as it relates to the packaging aspects of the product. Therefore, a characterization test regiment is typically designed to assess the components performance and any failures as a result of operation under those conditions.

Lastly, research and development products must be designed to withstand the radiation environments of space. Electrons, protons and ions in space can cause permanent damage in some types of electronic devices that can lead to operational failure. Utilization of research and development products in space applications may necessitate test and characterization of devices to determine their performance under a specific radiation environment and test conditions.

Figure 1 illustrates how the current transfer ratio – the critical parameter for optocouplers – varies among various lots of 4N49-type optocouplers. The key point is that there are large lot-to-lot variations. The two date codes produced in 2001 are considerably different, and are so severely degraded by proton fluence equivalent to about 2 krad (Si)

that lot sampling is required in order to use these devices in most space systems.

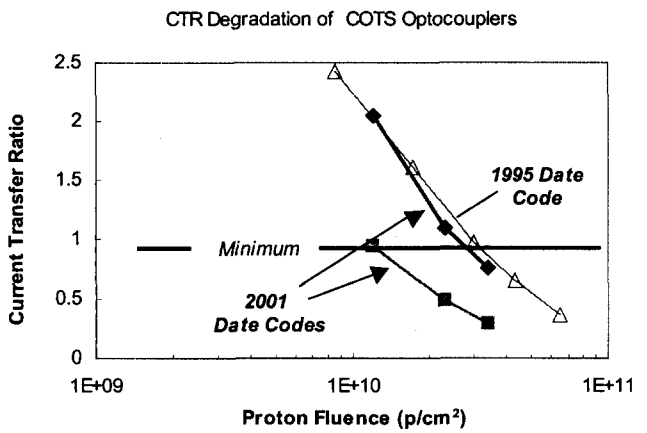
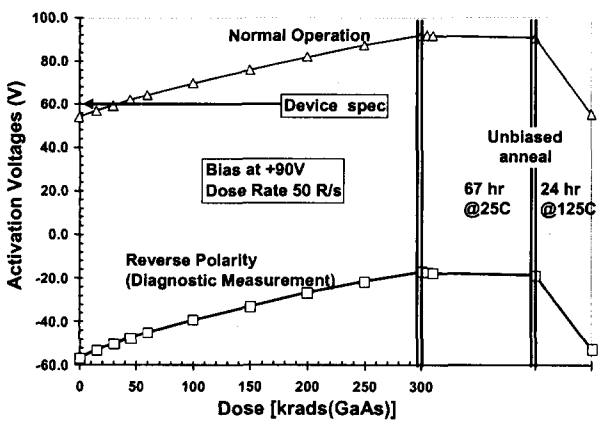


Figure 1. Radiation effect on the current transfer ratio for 4N49-type optocoupler from 2 different date codes [3].

Figure 2. shows the results of radiation studies on MEMS RF Relay under development [4].



The main difficulty faced by high reliability users is the implementation of small processing change resulting in a small performance impact in an earth environment, but a serious impact under a space radiation environment. This presents a very serious obstacle to wide utilization of research and development products in space systems.

Standard practices at JPL require all parts to be evaluated for radiation Total Ionizing Dose (TID), Displacement Damage (DD) and Single Event Effect (SEE) sensitivity, relative to the radiation requirements of the specific application. Where no radiation data are available, all candidate radiation-sensitive parts are required to undergo characterization testing and/or lot acceptance testing or be shown by analysis based on test data to be compatible with the application radiation levels. Radiation data should show 90% confidence that the population probability of survivability is at least 99%. Achieving this confidence is a very time consuming and costly option, but given the wide variability in the radiation tolerance of microelectronic devices designed for the commercial sector, it is the only viable option.

IV. CONCLUSIONS

The high performance needs of today's space systems necessitate the use of products from specialty research and development facilities.

Statistically meaningful techniques and methods for test, characterization and reliability evaluation of research and development products to determine suitability to space applications are necessary with the emphasis on the intended application and environment.

V. Acknowledgement

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VI. REFERENCES

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