Reliability Prediction of Radiation Induced Failures in Semiconductor Packages

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Abstract

The growth and usage of semiconductor components has risen greatly due to evolution of applications in industries such as aerospace, defense, and automotive, in both the commercial and government sectors. Among the different types of components that make their way into such applications, digital logic and memory-based devices are of prime importance due to the ever-demanding need to store and compute vast amounts of data. This brings to the forefront the reliability of such components, especially in demanding applications in aerospace and defense where components are exposed to extremely harsh environments where high performance is critical. This is where we find that reliability is largely dependent on the susceptibility of semiconductor components to radiation induced effects - total ionizing dose (TID) and single event effects (SEE).

Optimization in design, process, and packaging could make microelectronics more reliable to the radiation effects. Packaging material and thickness affect the incident flux of radiation on microelectronics and can help mitigate both dose and SEE effects in electronics. Additionally, packaging materials should not generate a high flux of secondary particles when exposed to environmental radiation (an example is alpha emissions from impurities in package mold compound or underfill).

In this paper, the behavior of semiconductors at the component level due to radiation effects is evaluated. A reduced order model approach is presented where the analysis is performed at the functional block level then aggregated into component. The behavioral model can be used to predict the behavior across different operating, design, and process conditions.

Key words: Radiation, TID, SEE, Susceptibility, Semiconductor, Reliability.

I. Introduction

The advent of microelectronics in all the emerging applications has given rise to several opportunities as well as challenges. One of the major reliability challenges has been radiation induced failures impacting not only space applications but terrestrial as well. There are two main types of failure mechanisms, total ionizing dose (TID) and single event effects (SEE). TID is a cumulative failure mechanism due to accumulation of damage over time resulting in degradation of device properties and eventual failure. SEE on the other hand is caused by transient effects of a particle strike resulting in soft or hard failures. To mitigate these effects, a novel, fast and cost-effective solution needs to be devised that is alternate to physical testing. In this paper, an integrated multi-physics approach is presented that provides the user with a reliability estimate of semiconductor designs taking into consideration the device, package, and environmental effects. Advantages of this approach include:

- Complexity of the component broken down by functional blocks and sensitive devices
- Parametrized approach to explore boundary conditions of the operating parameters
- ROMs capture the essential behavior of 3D TCAD simulation
- ROM extraction allows for model size reduction and obfuscation of any IP details
- Direct correlation with physics-based simulations ensures customer is receiving most accurate failure rate prediction for their mission profile

II. Methodology

This section provides an overview and highlights the importance of different aspects of the workflow and how they all contribute to the overall reliability of the component.

A. Radiation Environment

Objects in orbit experience differing exposure to particle radiation based on the orbital altitude and inclination. Modeling of radiation environment that covers a wide spectrum, from low Earth orbit (LEO) to geo-synchronous Earth orbits (GEO), was considered for this work. The major sources of particles in the space environment (Fig. 1) are galactic cosmic rays (GCR) from interplanetary space and solar flares from the Sun. Data on GCR, trapped protons, trapped electrons, and Solar Particle Events (SEP) can be obtained from publicly available databases.

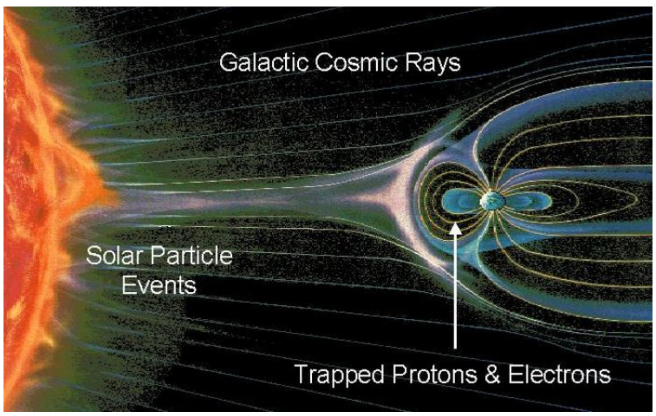

Fig. 1. The major sources of particles in the space environment [1]

It is interesting to note that levels of radiation vary significantly by orbit, largely due to the Van Allen belts. For example, exposure ranges from less than 100krad(Si) / year in a low Earth orbit (LEO) with high inclination (near polar) as compared to more than 700krad(Si) / year for a low inclination (near equatorial) orbit at 7,500km altitude. The striking difference in radiation exposure above the Earth is illustrated below in Fig. 2, a line plot of radiation intensity by inclination across the full range of low-Earth, mid-Earth, and geosynchronous orbits overlaid onto a colorized image of ionized radiation intensity due to the Van Allen belts. Clearly, orbit-specific environmental effects must be carefully considered for electronic components to survive their intended mission lifetime. Calculation of failure rates requires accurate knowledge of radiation flux received by the device material under consideration.

The platforms used for the purpose of extracting particle flux distribution in space environment are SPENVIS and CREME96.

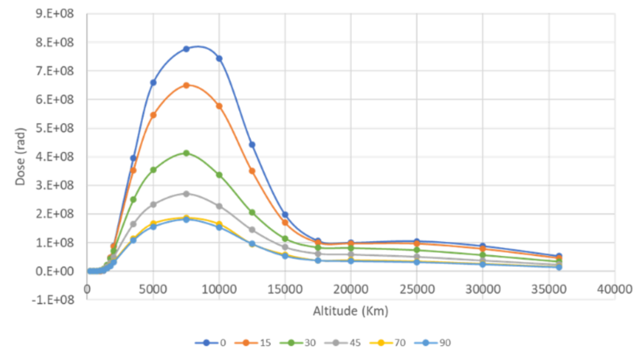

Fig. 2. Visualization of total ionizing dose by orbital altitude and inclination

B. TID Workflow

TID effects are cumulative and are caused when excess charge is trapped in the dielectric layers which cause the electronic device's degradation. Workflow for reliability analysis is shown in Fig. 3 which for TID is based on degradation of the device sensitive parameters and its effect on the reliability of the device.

SPENVIS radiation model is used to interpolate the annual dose based on altitude, inclination, package material, and shield thickness. A radiation model behavior at a very discrete level is first characterized using TCAD simulations in the absence of radiation (pre-exposure) and also in the presence of radiation (post-exposure).

The approach used to estimate reliability metrics, described in section III.B, is non-destructive degradation leveraging Weibull distributional analysis. This approach was chosen because the sensitive devices themselves are not failing but simply changing with cumulative dose.

C. SEE Workflow

There are several types of single event effects depending on the nature of device element and effect of particle distribution within the device. Workflow for single event upset (SEU) is shown in Fig. 3.

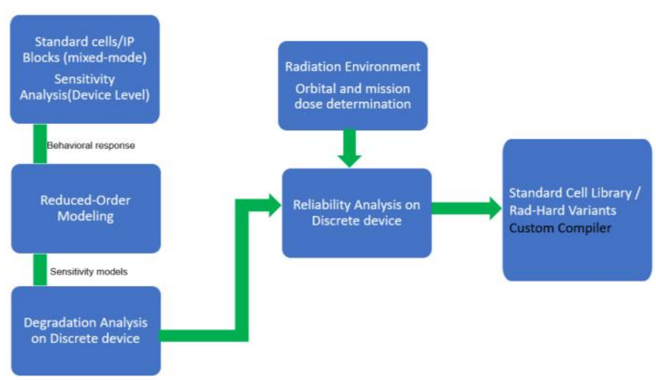

Fig. 3. Workflow for TID and SEE

Standard cells are basic building blocks that IC designers use to build up functionality as blocks and in turn full chip. To assess the impact of a particle, strike due to radiation on an IC component, sensitivity and behavior at a very discrete level must be first characterized [2]. TCAD simulations are ideal to determine the behavior and it is typically performed using the impact of particle strike with range of increasing energies typically referred as LET or linear energy transfer. A raster scan of particle energies across the surface area of the smallest element or standard cell will provide behavioral response of the device due to the strike. A reduced order model depicting the behavioral response of the data collected will then be created.

From the ROMs, degradation of the standard cell to the particle is determined in the form of a cross-section curve which is an indication of the sensitivity of the cell to range of particle energies. The radiation environment provides particle flux distributions at any given orbital conditions such as altitude, inclination, and shield thickness. Reliability analysis combines it all together providing a lifetime estimate of the component over the mission conditions and duration.

D. Packaging/Shielding

In a space environment – and where the mission dictates time and distance in the radiation environment – the only recourse is to mitigate or reduce the exposure levels to shield the electronics. Radiation shielding usually consists of single or multiple barriers of metal, ceramic plates, or enclosures. The type of shielding depends on the type of radiation to be shielded and its energy. The actual impact of shielding depends not only on the shield material and thickness, but also on the type and energy spectrum of the radiation being shielded against. As an example, electrons are shielded relatively easily by thin metal shields, while neutrons require meters-thick shields to reduce their numbers. In the space environment, shielding can help mitigate dose effects in electronics and human body doses in space crews. However, space radiation extends to extremely high energies, so shielding is never completely effective.

Another severe constraint in spacecraft is the mass and size of the final payload or vehicle. Large, heavy shielding is often not a viable option due to mass/space constraints. In typical spacecraft applications, the shield material is usually aluminum, with thicknesses of 100-300mils (2.5-7.6mm). Aluminum shielding does attenuate low-energy ions and electrons but has a minimal effect on high-energy radiation from galactic cosmic rays. Aluminum thicknesses in excess of ~50mils absorb the majority of incident electrons. However, increasing the shielding thickness beyond that renders diminishing returns. Fig. 4 illustrates the TID in low Earth orbit as a function of aluminum shield thickness for three space radiation sources (electrons, protons, and Bremsstrahlung radiation). The saturation in the curve means that adding additional shielding thickness is of limited effectiveness in further reducing TID. The saturation occurs because a large fraction of the incident proton radiation is of such high energy that several millimeters of aluminum are insufficient to significantly reduce their numbers [3].

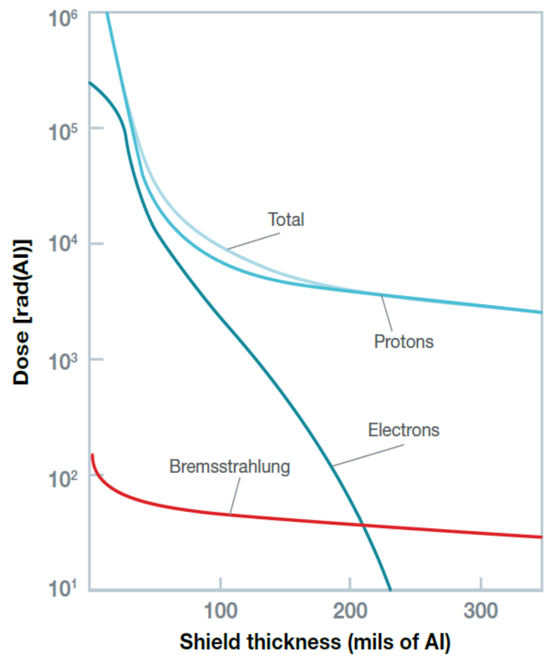

Fig. 4. Plot of total ionizing dose in low Earth orbit as a function of aluminum shielding thickness for three space radiations: protons, electrons, and Bremsstrahlung [3]

Effective shielding materials for different specific particle radiations encountered in industrial/medical environments are shown in Fig. 5.

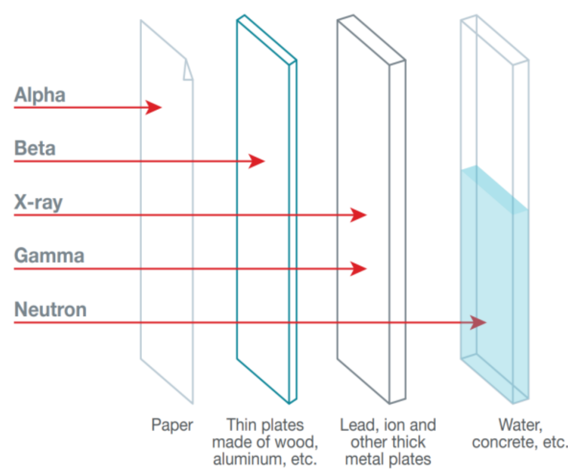

Fig. 5. Effective shielding materials for different specific particle radiations [3]

E. Sensitivity Analysis

Sensitivity analysis is the critical part of the overall workflow. It determines the impact the device is going to have on the overall functional block and component.

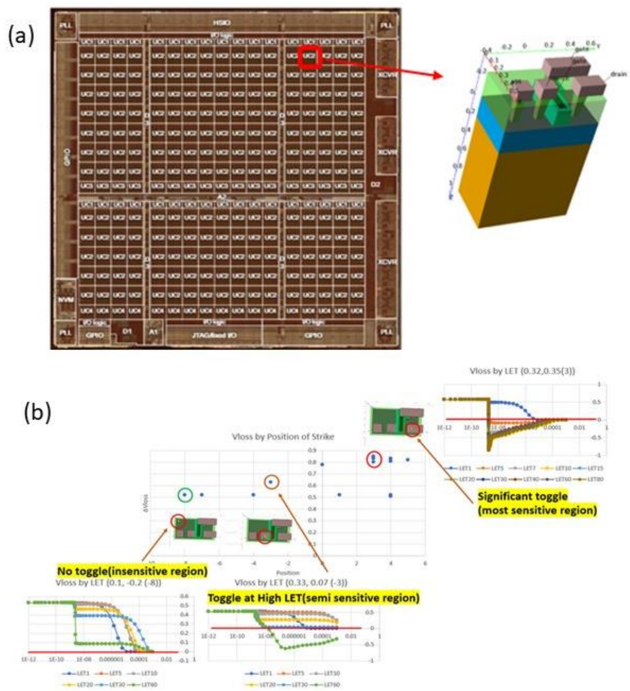

Fig. 6. (a) Identification of a discrete device from full chip (b) Sensitivity analysis of a SRAM cell

Full chip design can be broken down into smaller sub-blocks called functional blocks which perform specific functions based on circuit elements built using discrete elements called standard cells. To understand the impact at component level, sensitivity must be first understood at discrete level. There are certain functional conditions which are considered the worst case for behavioral response of a particle impact.

Design of experiments (DOE) is designed taking into consideration different functional, strike and physical/geometric conditions and they are executed by simulation runs in TCAD. The response of simulation runs are typically electrical parameters such as transient voltage, current, charge, to name a few.

F. Reduced Order Model

The vast amount of data being generated from simulation runs needs to be transformed into a model describing the behavior of particle strike and a corresponding response.

The models can then be used in the degradation analysis which is a process to calculate the number of upsets for range of LET's and in turn create the cross-section curve of the device as shown in Fig. 7.

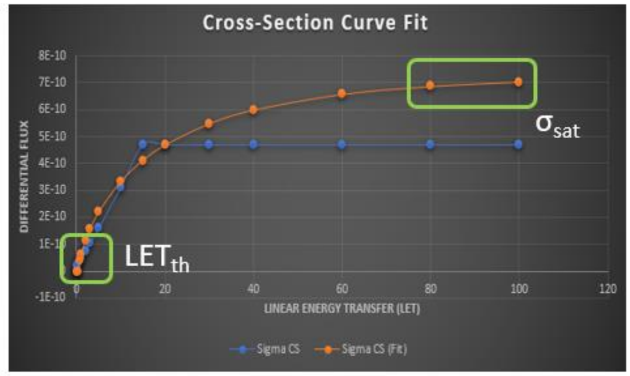

Fig. 7. Cross-section curve of SEE analysis

III. Results

The reliability analysis combines the sensitivity information determined from the previous analysis with the environmental models to calculate the failure rate. The approach is different for SEE and TID analysis and they are outlined below.

A. TID Reliability Analysis

Models developed for the sensitive devices were validated against published test results. As an example, TID analysis was performed on a 140nm commercial DRAM (part number: V54C3256164VD) and the results were compared against TID test report in [4]. Based on the TID test report, the mean retention time shifts down from ~2800ms (baseline value) to ~1300ms at 60krad. Table I shows that the calculated baseline and post-rad retention times based on the TID model are very close to the measured values in [4].

Table I. Comparing degradation in retention time from TID model to published data for a 140nm DRAM

	TID Analysis	Published Values [4]
Technology node	130nm	140nm
Bias	Off	Off
Sensitive parameter	Retention time (ms)	
Baseline value	2543	2800
Post-rad 60krad	1260	1300

The approach used to estimate reliability metrics is non-destructive degradation leveraging Weibull distributional analysis. To determine the Weibull parameters of η, β, and γ, a series of scenarios was run for each failure mode where the environment, dose, shield thickness, and critical degradation are varied. Mathematical models were established based on the training data. Degradation analysis was performed on the sensitive parameters in the functional blocks. The effect of sensitive parameters inside a functional block were combined to calculate the threshold failure rate of the functional blocks. An example of a functional block failure rate is shown in Fig. 8, the blue curve is the failure rate of a Configurable Logic Block (CLB), Digital Flip Flop (DFF) functional block, and the red line is the calculated threshold failure rate (TFR) value. The intersection is depicted by the black line which is the threshold failure dose (TFD).

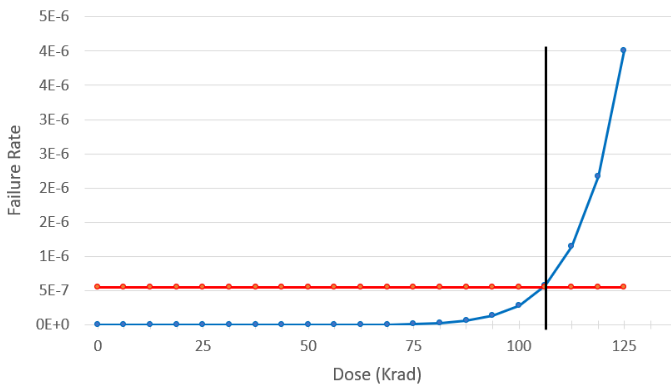

Fig. 8. Failure rate, TFR, and TFD of CLB-DFF functional block

B. SEE Reliability Analysis

The goal of reliability analysis is to calculate the failure rate of the device. The environmental analysis results in the creation of differential flux distribution for a cocktail of particle distribution for a given orbital condition. Numerical integration of flux curve with the cross-section curve across a range of LETs as shown in Fig. 9 provides the event rate of the device. This failure rate projected over a period of time results in reliability life prediction of the device.

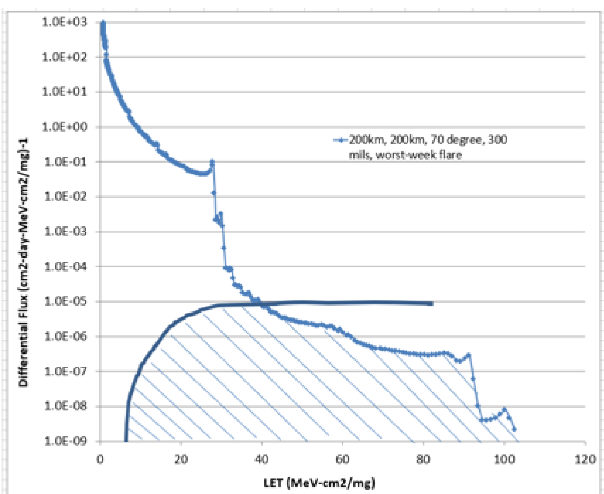

Fig. 9. Failure rate determination for SEE

Table II compares the results of a SRAM cell failure analysis calculated using the approach presented in this paper to published test data [5].

Table II. Failure rate comparison of model prediction and published test results

Data Source	Tech Node	Environment	Shielding	σsat	Failure Rate (upsets/dev/day)
Manufacturer A (Test)	65nm	GEO (35,000 km)	100 mil Al	3.00E-09	4.00E-08
Model	65nm	GEO (35,000 km)	100 mil Al	5.69E-10	4.35E-08

IV. Conclusion

The approach presented in this paper addresses some of the major industry pain points such as challenges with testing because it is very expensive and there are huge backlogs at limited test facilities. Also, obtaining design and process parameters are difficult due to lack of availability of Intellectual Property (IP) for full chip. The proposed methodology is cost effective and can be done at standard cell/functional block level or full chip level to determine the sensitivity of radiation effects and calculate the lifetime for the chip's operating conditions.

Acknowledgment

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