Implications of Advanced Microelectronics Technologies for Heavy Ion Single Event Effect (SEE) Testing

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Abstract--The complexity of SEE testing for space applications, has increased over the years. This trend has been mainly driven by advances in integrated circuit technologies. This paper reviews how the test environment relates to the real space environment. It shows that medium energy beams (25 to 200 MeV/amu) are more and more necessary for SEE testing of state-of-the-art microcircuits.

I. INTRODUCTION

The complexity of SEE testing for space applications has increased over the years. This trend has been mainly driven by advances in integrated circuit technologies. SEE testing of state-of-the-art devices has raised many issues [1]:

- delidding processes for devices encapsulated in plastic material,
- increased complexity of the functions to test,
- increased number of the input and output interfaces,
- increased clock speed,
- increased SEE sensitivity and new phenomena [2].

Shortcomings of SEE ground testing have been widely discussed [1], [3], [4]. In this paper, we focus on how heavy ions used for SEE ground testing relate to the actual space environment. We review the basic concepts and assumptions that underlie SEE ground testing techniques using various ions to simulate the space radiation environment. The limitations of these concepts for state-of-the-art devices are then presented.

II. SIMULATION OF THE SEE SPACE ENVIRONMENT AT GROUND LEVEL

Fig. 1 shows representative Galactic Cosmic Ray (GCR) energy spectra as modeled by CREME96 software [5]. CREME96 is considered to be the best available model for this application. Its limitations are discussed in [6]. GCR particles are always present, but their intensities vary with the solar cycle. During solar minimum, GCR intensities attain their highest levels and during solar maximum they are at their lowest levels. The most important characteristic of GCRs is their very high energy (up to several GeV per nucleon). They are highly penetrating in terms of spacecraft shielding.

![Cosmic Ray Energy Spectra](image)

Fig. 1: Representative Cosmic Ray energy spectra, CREME 96 solmin.

The Fig. 2 shows representative solar energetic particle spectra. Note the very large fluxes (compared to GCR) at low energies and the very rapid decrease of the flux with energy. Because the solar particle spectra are comparatively soft, typical spacecraft shielding does have a more noticeable effect.

Ion beams dissipate energy in matter through a series of collisions with the atoms of the material. In microcircuits ionization leads to the creation of a dense plasma of electron-hole pairs along the ion track. Existing electric fields then transport the deposited charge to various nodes. In the study of SEE effects in microcircuits, it has become customary to describe the ion radiation quality by the amount of energy lost per unit length of track, or the Linear Energy Transfer (LET). As each material has a unique
ionization potential, the LET is easily converted to a charge deposition rate. For example, in silicon, a charge deposition rate of 1 pC/µm corresponds to a LET of 98 MeV/(mg/cm²).

It is possible to obtain the same LET for different types of ions and energies. However, if it is assumed that all ions of a given LET have the same effect on the circuit, a LET spectrum can be used to estimate the upset rates in space. Such a characterization is called a Heinrich spectrum [7].

The GCR integral LET spectrum for silicon is shown in Fig. 3 along with contributions of some individual species. The lightest ions are dominant in the lowest LET (0.1 to 1 MeV/(mg/cm²)) part of the spectrum. The heaviest ions are dominant in the highest LET part (30 to 100 MeV/(mg/cm²)). However, the fluences in this latter portion are very small. For LETs from 1 to 30 MeV/(mg/cm²), the LET spectrum is dominated by the Fe and Ni ions. The Solar Particle Event (SPE) integral LET spectrum is shown in Fig. 4. The lowest LET part of the spectrum is dominated by protons and alpha particles. Similar to GCR, the heaviest ions are dominant in the highest LET (> 30 MeV/(mg/cm²)) range of the spectrum, but their overall contribution is extremely small. In the medium LET range (1 to 30 MeV/(mg/cm²)), Fe is the most significant ion.

As the SEE sensitive regions of many microcircuits are relatively thin (several µm), ground testing is conducted using ions with lower energies than GCR, but with similar LET. The energy range at the SEE facilities commonly used [8,9,10,11] is of the order of several MeV/u and the range of ions is about from 30 µm for the heaviest particles to 100 µm for the lightest particles.

The use of different angles of incidence is used to vary the energy deposition in the sensitive volume of a microcircuit and therefore obtain more experimental measurements with the same ion. This gives rise to the concept of effective LET, which assumes the energy deposition is determined by the incident particle’s LET and its angle of incidence. However, this does not account for several factors that may influence the measured results. First, this concept may not be valid for low energy ions because the LET value may decrease as the ions traverse the sensitive region. Secondly, the concept does not...
account for statistical fluctuations in the energy deposition process. Thirdly, it assumes that effects due to ion track structure are negligible. Quantitative estimates of these last two effects have been discussed in [12]. Finally, it assumes that the sensitive volume is a thin parallelepiped. Some SEE, such as SEB and SEGR cannot be correlated with tilt angle [13].

When the GCR LET spectrum is defined and the SEU cross section curve versus LET is measured, the upset rate can then be calculated assuming a Rectangular Parallelepiped (RPP) sensitive volume and a constant LET in this sensitive volume [14].

III. DISCUSSION AND EMERGING ISSUES

As discussed in the preceding section, an incident ion’s LET is usually assumed to be a valid parameter for describing SEE effects in microcircuits. But in modern devices, sensitive volumes are very small and there may be a strong difference between the energy lost by the ion and the energy locally deposited in the sensitive volume. The ion LET (and effective LET) overestimates the energy deposition as shown in Fig. 6. This Figure shows the fraction of an ion’s energy loss as a function of the volume’s average chord length (ie the average travel length of the particles in the sensitive volume) for different incident ion energies [12]. We can see in the figure that the smaller is the sensitive volume and the higher is the ion energy, the higher is the overestimation. Then, charge collection is a complex phenomenon affected by the size of sensitive regions and the structural arrangements of multiple junctions. Therefore, it is controlled not only by the characteristics of the incident ions [15] but also by geometrical arrangement of junctions and the properties of the semiconductor material.

Figure 6: fraction of an ion’s energy loss within the sensitive volume as a function of the volume’s average chord length for different incident ion energies [12].

In addition, the use of low energy ions for SEE testing introduces experimental limitations: LET variations over the sensitive volume, low range inducing angle effects and limiting the funneling charge collection. Comparative SEE testing studies with high and low energy ions have shown that standard low energy test methods were adequate to test previous generations of microcircuits (down to 0.5 μm feature size) [16, 17]. But, discrepancies have already been observed in high density microcircuits and vertical sensitive volumes like DRAMs [18,19].

Another significant factor that must be considered for SEE testing of modern microcircuits is to use ions that reach the sensitive regions. Some devices can have up to 5 metallization layers, and are constructed with a metal lead frame extending over the die. Others have the entire die encapsulated in plastic material [20]. Plastic removing techniques have been used with success for several years, but removing the lead frame of a DRAM is a much more complex operation. These factors have resulted in the need for ions with a longer range (ie of higher energy) to penetrate to sensitive regions through plastic, lead frames and/or metallization layers. It is not uncommon now to have to go through on the order of 100 μm of material before reaching the sensitive region of a device (for example the thickness of a lead frame on a 64M DRAM is about 150 μm). For certain types of devices such as flip chip devices, this thickness could be even greater. The heavy ion accelerators currently used for SEU testing can not deliver this range.

Because of the complexities of the charge collection process and new package technologies in advanced microcircuits, it is becoming more and more necessary for SEE testing to use ions with an energy range representative of the SEE space environment.

Fig. 7 shows the ratio of particles of low energy (0.1 to 25 MeV/u), medium energy (25 to 200 MeV/u) and high energy (> 200 MeV/u) in the GCR LET spectrum. We can see in the Figure that high energy particles dominate the low LET part of the spectrum, but are negligible for LET greater than about 3 MeV/(mg/cm²). The low energy particles, (the particles having similar energy range to those often used for SEE testing) dominate the high LET spectrum from about 10 MeV/(mg/cm²) to 100 MeV/(mg/cm²). The medium energy particles dominate the LET spectrum from about 1 to 10 MeV/(mg/cm²).

Figure 7: repartition of low, medium and high energy ions in the GCR LET spectrum.
Above a LET of 10 MeV/(mg/cm²), space heavy ions have low or medium energy, and their range is limited. For example, for the Fe ion, above a LET of 28 MeV/(mg/cm²), the energy is less than 1.6 MeV/u and the range in silicon is less than 18 μm. As can be seen in Figure 3, Fe dominates the GCR spectrum for LETs between 10 and 28 MeV/(mg/cm²). This implies that most particles with LETs in this range that reach the sensitive structure have a limited penetration range, which turns out to be between 18 and 400 μm as shown in Fig. 5. This is consistent with the penetration range of particles used for ground testing for this LET range.

The most significant part of the LET spectra for advanced microcircuits is the range between 0.1 to 10 MeV/(mg/cm²). Most sensitive devices have a threshold LET less than 1 MeV/(mg/cm²) and their cross section reaches the saturation before 10 MeV/(mg/cm²). It has been shown that the threshold LET of microcircuits with sensitive volume dimensions less than micrometers has not changed significantly with the device scaling [2]. Therefore, except for optoelectronic devices, we do not expect in the near future threshold LET lower than 0.1 MeV/(mg/cm²), which implies that SEE can be produced by direct ionization due to protons.

Considering the incident particle energies, the most significant energy range is the medium energy range from tens of MeV/u to 200 MeV/u.

![Figure 8: available beams in facilities used for SEE testing.](image)

The Fig. 8 shows the maximum beam energies available in facilities used for SEE testing. We can see that the most currently used facilities (BNL, UCL, IPN) with a maximum beam energy lower than 10 MeV/u do not cover this energy range at all. LBL and Texas A&M facilities cover a part of this range. GANIL and MSU facilities give the best coverage of the medium energy range, but it is generally difficult and expensive to get some beam for SEE testing in these facilities.

IV. CONCLUSION

We have reviewed how the SEE test environment relates to the real space environment. Low energy beams are not representative of the most significant part of the space environment for modern microcircuits. Medium energy beams are a better representation of the space SEE environment, and they also give longer ranges to allow access to the sensitive volumes of modern devices. For these reasons medium energy beams are more and more necessary for SEE testing. These beams are not well covered in the existing facilities currently used for SEE testing.

V. REFERENCES