Use of Proton SEE Data as a Proxy for Bounding Heavy-Ion SEE Susceptibility

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Abstract: We examine use of proton SEE data to constrain heavy-ion SEE susceptibility. We discuss limitations due to short range proton recoils and develop an approach for using proton data to constrain on device sensitive volumes.

Introduction, Data and Method

Although heavy-ion single-event effects (SEE) pose serious threats to semiconductor devices in space, many missions face difficulties testing such devices at heavy-ion accelerators. Low-cost missions often find such testing too costly. Even well funded missions face issues testing commercial off the shelf (COTS) due to packaging and integration.[1,2] Some missions wish to fly COTS systems with little insight into their components. Heavy-ion testing such parts and systems requires access to expensive and hard-to-access ultra-high energy ion accelerators,[3] or significant system modification. To avoid these problems, some have proposed using recoil ions from high-energy protons as a proxy to bound heavy-ion SEE rates.[4-7]

While proton testing avoids the range issues of heavy-ion testing (see fig. 1), potentially producing ions with linear energy transfer (LET) up to 15 MeVcm^2/mg, bounding heavy-ion SEE rates with proton testing also poses challenges (see fig. 2). This is particularly true for destructive SEE.[8-11]

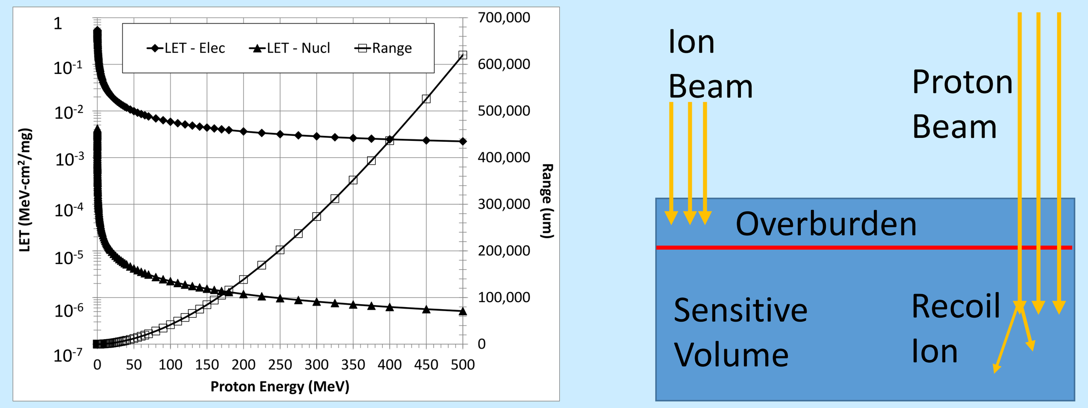

Fig.1 Heavy ions from accelerators impinge on devices under test (DUT) with a uniform energy and angle, so that if there is too much overburden, they range out before reaching the sensitive volume. Protons have much greater range. Although most protons lose energy slowly, a few interact strongly with nuclei in the lattice, generating ion recoils, which emerge with a range of energies, angles and even ion species.

The difficulty of bounding heavy-ion SEE rates with proton SEE data arises from the complex kinematics of proton-nuclear recoils. While [4-7] consider recoil ion production vs. ion species, energy and angle, the emphasis is on the LET spectrum of recoils. The authors conclude that irradiation with 10^{10} protons/cm^2 equates to heavy-ion testing up to LET > 8 MeVcm^2/mg.

However, describing space heavy ions in terms of LET oversimplifies the situation. For small (<<1 μm^3) SV, LET describes average energy loss, while SEE may result from rare events (energetic delta rays) that represent fluctuations away from the average indicated by LET.[12] Extreme events for high-energy ions deposit far more energy in a small SV than events of similar probability for low-energy ions. In large SV, LET varies along the ion track length, especially for low-energy ions, such as proton-nuclear recoils. Over 99% of recoils with Z>8 are on the low-energy side of the Bragg Peak.

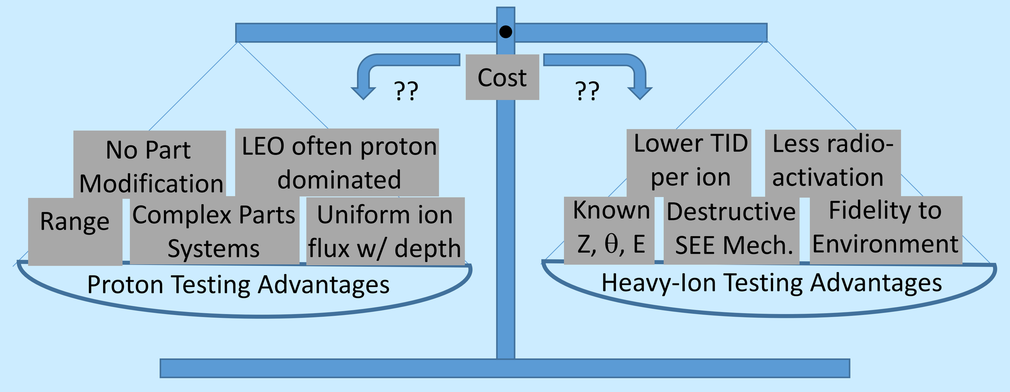

Fig. 2 Whether testing with heavy ions or protons is the preferred strategy depends on a variety of factors ranging from ion kinematics to part susceptibilities to questions of feasibility.

We use the CRÈME-MC physics based Monte Carlo package[13,14] on the Vanderbilt University Cluster to generate proton recoils and measure the energy they deposited in the SV of various dimensions characteristic of destructive and nondestructive SEE. CRÈME-MC uses the Monte Carlo Radiative Energy Deposition (MRED) package, which in turn uses the CEM03 nuclear code for proton-nuclear interactions. These codes have been validated extensively and found to be in good agreement with empirically measured cross sections.[15]

Destructive SEE Mechanisms

Destructive SEE (DSEE) modes are among the most serious threats facing many missions. They are also difficult to bound with proton data, since DSEE susceptibility depends on more than ion LET. See Figs. 3-4.

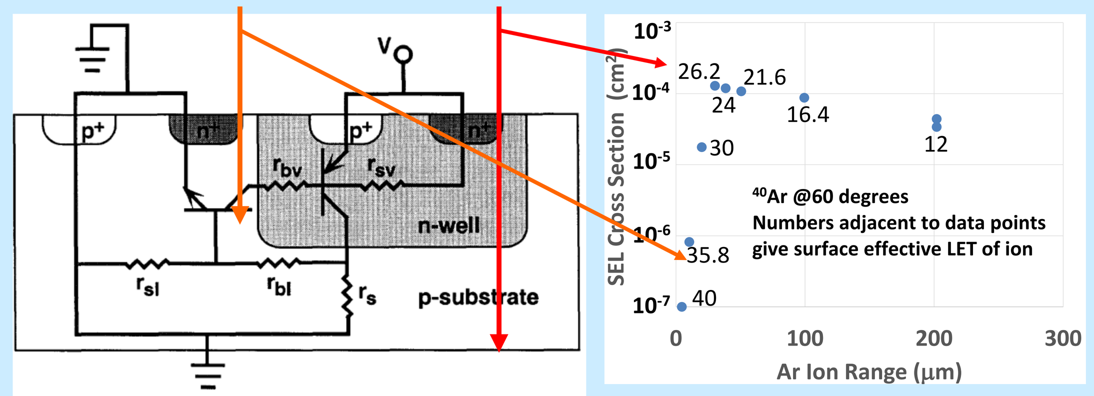

Fig.3 Since SEL is a parasitic bipolar phenomenon in CMOS devices that inherently involves the substrate, charge produced in the substrate contributes to the effect. Ref. [10] found that for cryogenic SEL at 20 K, short-range ions yielded cross sections >1000× lower than ions depositing a maximum energy in the SV, and that increasing ion range increased cross section up to a range of 35 microns. [11] noted similar effects for conventional (room temperature) SEL. Thus, using proton data will significantly underestimate the heavy-ion SELsusceptibility if it looks at ion LET rather than charge deposited by the ion.

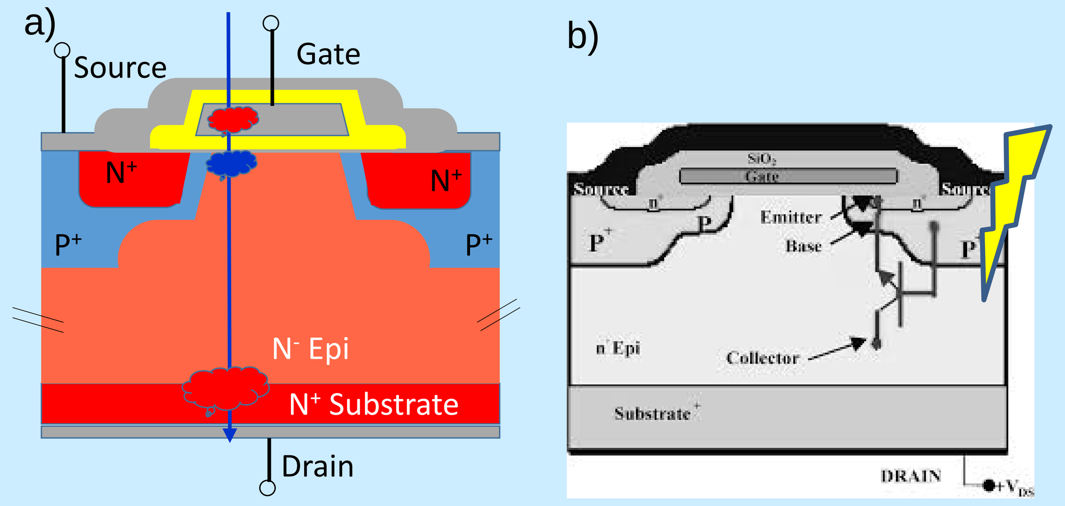

Fig. 4 a) SEGR depends not just on ion LET or charge deposited in the SV, but also on ion angle of incidence and atomic number Z. The angular and Z dependencies (likely the result of momentary gate oxide weakening by the ion), limit the number of proton recoils that can cause SEGR. Similar effects occur in FLASH memory[16] and some bipolar technologies.[17]. b) Like SEL, SEB is a parasitic bipolar effect. While ion range is usually less critical than for SEL and SEGR, [9] shows SEB voltage decreasing for short range ions (<30 μm). This work also suggests SEB vulnerability may increase with Z. These factors, along with the angular dependence suggest proton recoils will likely underestimate SEB vulnerability significantly.

Representative Sensitive Volumes

While DSEE SV have complicated geometries, simplified SV suffice to illustrate the difficulties of using proton data as a proxy for bounding heavy-ion SEE rates. We represented the SV as cubes surrounded by inert Si. (See fig. 5) The smallest SV was a 1 μm cube, roughly representative of charge collection volumes for nondestructive SEE. Although SV for deep submicron are smaller, we wanted to avoid situations where ions fluctuated significantly away from constant-LET behavior over short distances. The largest SV was a 10 μm cube. This is a fairly shallow charge collection depth z for DSEE. However, it demonstrates the problems arising from using proton recoils as a proxy for heavy-ion test data, and for any deeper SV, protons recoils would only deviate further accelerator or galactic cosmic ray (GCR) heavy ions. We defined an equivalent LET as the average energy deposited (E_{Dep}) in the SV normalized to the material density ρ:

$$LET_{EQ} = E_{Dep} / (\rho \times z)$$

An ion with this constant LET would deposit the same charge in the SV.

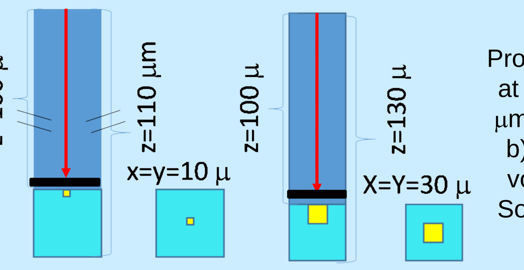

Fig. 5 Typical geometries used in the study. Protons follow the red arrow. a) A 1-μm cubic SV is at the top of a 10 μm inert-Si cube and below 100 μm of Si overburden for proton recoil equilibration. b) A 10 μm SV is located on top of a 30 μm inert volume of SI, also under 100 μm of overburden. Some runs also placed a 0.6 μm layer of either W or SiO_2 above (black line) the SV.

Results and Discussion

Figs. 6-7 illustrate the dependence of LET_{EQ} on proton fluence and the size of the sensitive volume. Regardless of the SV size, LET_{EQ} increases rapidly from 20-50 MeV, but flattens out from 100-500 MeV.

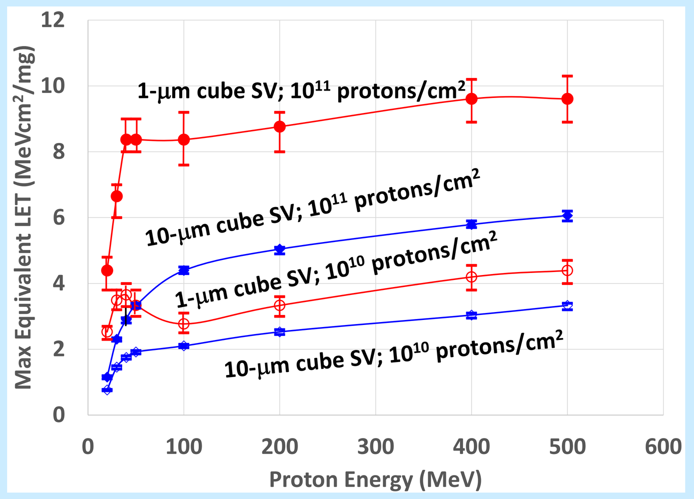

Fig. 6 Maximum LET_{EQ} for the given SV and fluence, and assuming the device heavy-ion cross section is 10^{-4} cm^2. Increase is rapidly at low proton energy, but slow above 50 MeV. This is because as energy increases, more of the recoils fragment, but more energy is transferred to the recoils. So while fewer recoil ions are range limited, energy deposited in the SV increases only slowly. For shallow SV, LET_{EQ} increases significantly as fluence increases form 10^{10} cm^{-2} to 10^{11} cm^{-2}, while less increase is seen for thicker SV. This indicates that charge deposited in thicker volumes is limited by the particle ranges rather than their LETs.

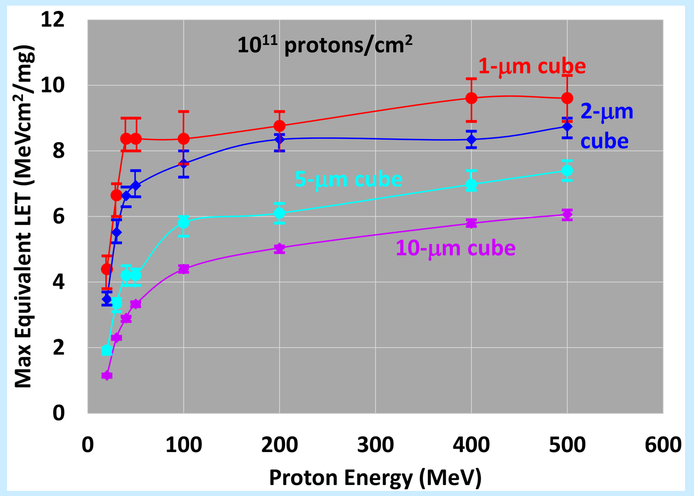

Fig. 7 As SV depth increases maximum LET_{EQ} decreases for all proton energies due to the short ranges of proton recoils. This not only lowers the bound on onset LET for heavy-ion susceptibility, it also decreases the cross section for the SEE (unless the σ vs. LET curve saturates at very low LET) . For SV deeper than 10 microns, the effect will be even more severe, since range limited ions will not deposit more energy in SV. The plot was generated assuming a device heavy-ion cross section of 10^{-4} cm^2.

Fig. 8 shows how small amounts of high-Z material (a 600 μ layer of W) can significantly increase the maximum LETEQ in the SV.

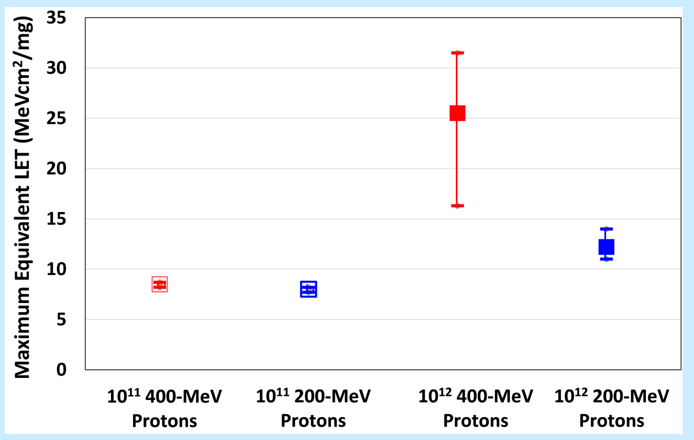

Fig. 8 High-Z materials can also affect maximum LET_{EQ}. A 0.6-μm layer of W over the SV can double the maximum LET_{EQ}, but only for large fluences of high-energy protons. For high-Z materials, most of the recoil energy comes from the fission of the original struck high-Z nucleus. As such, it depends on the nuclear decay physics to a very high degree. Lack of knowledge of which ions are responsible for an error and the nonhomogeneous dispersion of high-Z materials within the microcircuit significantly increase uncertainty of onset LET when high-Z materials are present.

The fact that the LET_{EQ} from this study are consistent with the LET found in [4-6] for shallow SV, but are significantly lower for deep SV suggests that the limited range of proton recoils is responsible for the differences rather than any differences in the physics models. To verify this, we combined differential energy cross section (figure 3 from [6]) with ion species production (figure 7 from [6]). The results in Fig. 9 suggest few proton recoils have energy higher than the Bragg peak. The chances of one of these traversing a long chord length in a deep SV are small.

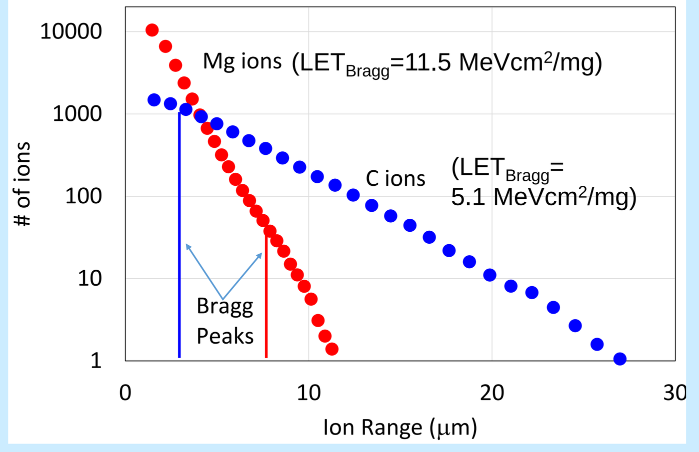

Fig. 9 Although [6] showed that 10^7 200-MeV protons in Si produces ~10465 Mg ions, over 99.7% have energy below the Bragg peak and a range<8 μm. Other ions with Z>10 have similar kinematics. The same fluence produces 1485 C ions, with the majority having ranges longer than the Bragg peak. However, the lower C ion LET means that despite longer range, C ions do not deposit more energy even in a deep SV. At lower proton energies, there are proportionately more ions at higher Z, but recoil energies are lower, while at higher proton energies, recoil ions have higher energies, but lower average Z.

Hardness Assurance Implications

The discussion of DSEE mechanisms and the Monte Carlo results paint a pessimistic picture for use of proton data to bound heavy-ion DSEE rates. The Z, angular and range dependence of SEGR and SEB suggest proton testing will significantly underestimate SEB/SEGR risk if it detects the susceptibility at all.

The situation is more favorable for SEL. However, improperly accounting for SV depth d can underestimate the SEL rate by >20× (for $d=10$ μm) for proton test fluences of 10^{10} 200-MeV protons/cm^2 or >5x if the fluence is 10^{11} cm^{-2}. If the charge collection depth is deeper (common for SEL), the underestimate will be even worse. Moreover, since SEL cross section scales with collected charge (and therefore LET_{EQ}), the area vulnerable to proton-induced SEL may be significantly smaller than would be assuming it scaled with LET.

For nondestructive SEE, charge collection volumes are shallower, and our results of would likely match those of [4-7] for SV sufficiently large that the constant LET assumption is valid. However, [12] showed that the broader charge-track distribution for high-energy ions can trigger error modes that would not be revealed by low-energy proton recoils. At the 22 nm node and below, this could be a significant concern for multi-bit upsets and upsets in hardened latches that rely on spatially separated redundant nodes for their hardening.

Generalized Linear Model

Although proton SEE test data can constrain heavy-ion SEE susceptibility, bounding destructive SEE modes remains problematic. The previous discussion has shown that the only DSEE mode where proton testing might provide useful bounds is SEL—and even then, a single-energy irradiation may not provide sufficient information about the SEL SV to bound the failure rate with confidence. Even for nondestructive SEE, a single-energy test is unlikely to place meaningful bounds on susceptibility in any but the most benign heavy-ion environments. This raises the question of whether multiple energies might be combined to improve the bounds. Recoils from low-energy protons tend to have Z>10 (and so, LET), but short range, while high-energy proton recoils tend to have numbers of ions with Z≤8 and Z>10, but have longer ranges. The result of these differences can bee seen in Fig. 8, where LET_{EQ} saturates at lower energy for shallow SV than for deeper SV. Thus, use of multiple proton energies could differentiate between candidate SV and better constrain SEE rates.

We assume that the cross section follows a Weibull and use a Generalized Linear Model to constrain the Weibull parameters and determine the heavy-ion cross section vs. LET curves that are consistent with the proton data to a desired confidence level as in [18]. However, because of the short range of most proton recoils, we parameterize the Weibull in LET_{EQ} rather than LET. For a range or proton energies incident on sensitive volumes with a given cross section σ and depth d, we used CRÈME-MC to generate the proton recoil LET_{EQ} distributions $\phi(LET_{EQ},E_p,d,\sigma)$. When stored as a look-up table, these distributions can serve as a CRÈME-MC emulator to determine which of the candidate SV are consistent with proton SEE data. It should be noted that the cross section of the SV changes with LET_{EQ}, while the depth, d, which is along the predominant direction of the proton recoil will not. Thus for a given proton energy E_p, a device with N_{SV} sensitive volumes of depth d will generate an expected number of events

$$\mu(E_p,d) = \int_0^{MAX(LET_{EQ})} N_{SV}\phi(LET_{EQ},E_p,d,\sigma(LET_{EQ})\times\sigma(LET_{EQ})dLET_{EQ}$$

We chose $\sigma(LET_{EQ})$ to be the Weibull form parameterized in terms of the limiting cross section σ_{lim}, onset LET LET_0, and the Weibull weight w and shape s. Observed events $N(E_p)$ will fluctuate about this mean according to the Poisson distribution, so the likelihood L for the GLM will be:

$$L(d,\sigma_{lim},LET_o,w,s) = \prod_{E_p} Poisson[N(E_p),\mu(E_p,d,\sigma_{lim},LET_o,w,s)]$$

Ideally, we would maximize L in terms of the parameters. However, usually, proton data will constrain the sensitive volume model only weakly, so it is unlikely we will be able to reduce the SV models that give an acceptable fit to a single best model. Rather, as in [18], it may be necessary to take as a bound the worst-case rate for any SV consistent with the proton data to a given confidence level.

Another approach would be to use proton data in conjunction with other data that constrain one or more of the SV model parameters with a Bayesian Prior.

Conclusions

We have examined the effect on device SV geometry on the conclusions that can be drawn from proton SEE data for heavy-ion SEE susceptibility. We find that for devise SV with depths greater than about 5 microns, charge generation by recoil ions from proton-ion collisions tends to be limited by the ion's range rather than its LET. This means that proton data place very weak constraints on heavy-ion induced SEL. Similar considerations apply for SEGR and SEB. However, dependence on ion angle of incidence and ion species for these failure modes mean that generalizing from proton data to heavy-ion susceptibility is risky.

We also propose a generalized linear model approach for using proton SEE data to bound heavy-ion SEE susceptibilities that allows data for several proton energies to be combined to draw more reliable conclusions about device SV geometries from proton data.

Acknowledgment

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