Latchup in Integrated Circuits from Energetic Protons †

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INTRODUCTION

Although latchup from heavy ions has been studied in considerable detail, much less is known about latchup from energetic protons. Proton latchup has been observed in relatively few devices, and the experimental evidence to date suggests that it is mainly important for devices with heavy-ion thresholds in the range of 2-3 MeV-cm^2/mg, a much lower range than that predicted by theory and elementary geometrical models. An LET threshold of ≈10 MeV-cm^2/mg is often used as an effective upper limit for concern about proton SEE phenomena [1,2], based on the maximum effective LET of Mg recoils.† Existing results for proton latchup suggest that this LET limit is far too conservative; however, as discussed later, it may be valid for more advanced structures with thin epitaxial layers.

This paper examines mechanisms and models for latchup from protons, as well as charge collection in the underlying substrate region. Two devices for are used as examples: the HM65 162, a 16k SRAM; and the National 32C016, a microprocessor. Spreading resistance measurements were made to determine the underlying structure of these devices. Figure 1 shows the carrier concentration in the n-well and underlying p-substrate region for both devices. The HM65162 has a bulk substrate, and the 32C016 has an epitaxial substrate that extends nearly 10 μ beyond the well, with a very broad transition region. In both structures, the largest contribution to charge collection from long-range particles is from the substrate, not the well region, because the substrate is much more lightly doped than the well.

For shorter range recoil products from proton reactions, charge collection is not as straightforward. Simulations with PISCES were used to calculate charge collection for ions with different track lengths in a bulk substrate in order to compare charge from long- and intermediate-range ions in these structures. A cylindrical geometry was used for the simulation with 5-V reverse bias. Figure 2 shows an example of these simulations for a bulk substrate; the full paper will include simulations for epitaxial structures as well as for different doping levels. The range of the particle must extend well beyond the effective charge collection depth in order to collect the maximum charge (note the difference in charge for track lengths of 35 and 100 pm). For ions with shorter range, such as proton recoil products, only about 25% as much charge is collected at time periods > 20 ns compared to that collected from ions with long range with the same LET.

Several simulations were done with short tracks at locations various distances below the top surface. The same charge was collected as long as the entire track was located within the depletion region. However, if part of the track was placed outside the depletion region (either in the well or the substrate) nearly all of the charge in the track that was outside the depletion region was not collected. Only charge near the bottom of the n-well (approximately the last 0.5 pm) contributes to the collected charge. Thus, most of the top layer of the well is a "dead" region from the standpoint of charge collection for short-range tracks, and charge collection is dominated by charge produced in the substrate.

HEAVY-ION AND PROTON LATCHUP CROSS SECTIONS

Heavy-ion cross sections for these two devices are shown in Figure 3 (data for the HM65 162 are from Levinson, et al. [3]; results for the 32C016 are new). For both devices, the heavy-ion cross section first becomes significant for LET values of about 2 MeV-cm^2/reg. In both cases the cross section increases as LET increases. The HM65 162 cross section has a broad shoulder, continuing

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to increase over a wide range of LET values.† At 6 MeV-cm^2/mg the cross section of the HM65 162 is 20 times larger than that of the 32 C016. The heavy-ion data would lead one to expect the cross section of the HM6516 to be considerably higher than that of the 32C01 6 when it was irradiated by protons with sufficient energy to create significant numbers of recoil products with LETs in the range where the heavy-ion cross section rises sharply. However, the actual proton results are exactly opposite, as shown in Figure 4.†† Although the proton cross section of the HM65 162 continues to increase at high energies, its cross section is well below that of the 32C0 16, even at 300 MeV.

The ratio of the heavy-ion and proton cross sections and their dependence on LET and proton energy, respectively, provide additional insight. As proton energy increases, the maximum energy of the recoil products increases along with the relative number of particles with a given energy (see Figure 5, after El Testy, et al. [5]). The proton cross section should increase rapidly as the proton energy increases because the heavy-ion cross section increases so strongly, at least in the region where the effective LET values of proton recoils overlap the region where the heavy-ion cross section increases rapidly. Again, the results are the opposite of that expected. Although the proton cross section of the HM65 162 increases somewhat, it actually changes by a smaller amount than the heavy-ion cross section; that is, the ratio of the proton cross-section to the heavy-ion cross section decreases at higher proton energies. This suggests that the effective LET of the proton recoils is considerably lower than that expected in this energy range.

LATCHUP SENSITIVE VOLUME

Physical models for proton latchup have been developed by extending the concept of sensitive volume that has been developed for single-event upset to single-particle latchup [3,6,7]. Although it is possible to arrive at an effective volume with such an approach, the results are physically inconsistent with charge collection and triggering processes that are involved in latchup from heavy ions and proton recoil products, and tend to dramatically underestimate the charge collection depth. These models have generally assumed (1) charge generated in the relatively shallow isolation well produces the charge that triggers latchup, whereas in reality charge generated in the substrate is the dominant component; (2) the entire well area contributes to the cross section; and (3) a constant sensitive volume near threshold. None of these accurately reflect the charge collection and triggering processes involved in latchup. For example, Levinson, et al. [3], obtained an effective charge collection depth of 2 µm for the HM65 162. This is much less than the range of recoil products and is inconsistent with the calculations in Figure 2.

Experimental and modeling studies of heavy-ion latchup have shown that near threshold, when the charge is just sufficient to initiate latchup, only a small fraction of the well region is involved [8-10]. The most sensitive region (or regions in a complex structure) is the region farthest from the well contact, because the voltage drop within the well is largest for an ion that strikes far from the contact [9]. Unlike single-event upset, latchup involves a secondary step: the vertical transistor must be turned on by the voltage drop of the transient current in the well, and thus depends on the position of the ion strike within (and under) the well. This introduces a geometry dependence that has no equivalence in single-event upset.

Because ions with LET (or total deposited charge) above the threshold can cause latchup to occur in regions of the well that are closer to the well contact than ions at threshold, the effective area of the well increases rapidly for ions with LET above the minimum LET for triggering. Thus, the well area is a "moving target," particularly for ion strikes that deposit energy slightly above the threshold.††† This is evident from the strong energy dependence (and very low cross section) for proton latchup in

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†In most cases, latchup cross sections do not saturate because of charge diffusion. Multiple latchup paths and different well geometries further complicate the LET dependence.

††The cross section for the 32C016 differs from earlier data by Nichols, et al. [4] due to an error in the figure showing the proton cross section. Results in Figure 4 are new data for the same devices reported in the earlier work.

†††Consequently the charge collection volume for latchup is not constant. The assumptions used in modeling proton SEU with constant charge collection regions or Bendel parameters are not applicable to latchup.

the HM65 162, as well as from test structure studies [8]. The low proton cross section of the HM65 162 compared to that of heavy ions is due to the fact that the charge collection depth (average effective depth for ions with long range) for heavy ions is nearly 20 pm,; the short-range proton recoils have a much lower effective LET when compared with long-range particles. The proton cross section of the 32C016 not only has a much higher ratio compared to the cross section for heavy ions, but also has a much different energy dependence. The epitaxial substrate of the 32C016 cuts off the charge collection, causing the proton cross section to approach saturation for proton energies above 100 MeV. Even though the 32C016 is an older device with a relatively thick epitaxial layer, it illustrates how scaling and reduction in the charge collection depth is likely to affect latchup.

Figure 6 compares the effective charge collection depth for long-range particles for devices on bulk substrates. PISCES calculations were used to determine the charge, assuming a 25 ns triggering time for latchup. The epitaxial substrate of the 32C016 reduces the effective charge collection depth by more than a factor of two compared to a bulk device with the same doping density, so there is a closer equivalence between the LET of heavy ions and intermediate-range recoil products than for devices with bulk substrates. Modeling results and the difference in the cross sections for these two devices suggest that the shorter charge collection region of more modern devices will result in higher proton latchup cross sections, as well as a higher incidence of latchup from protons for devices with LET thresholds of= 8-10 MeV-cm^2/mg. Although the 32C01 6 is an older device, the epitaxial thickness is small enough to show how charge collection affects comparisons between heavy-ion and proton latchup. The full paper will include proton latchup test results and modeling for additional devices. Lateral well geometry and contact placement, which are key factors in latchup susceptibility[1 1], will also be included.

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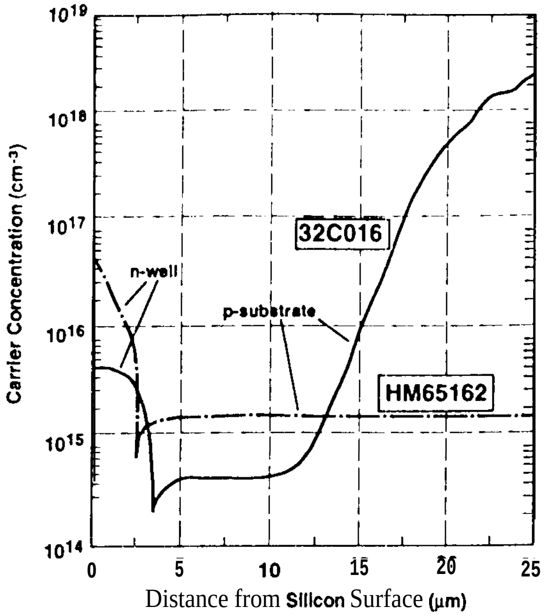

Figure 1. Doping Profile of the Well and Substrate Regions of the Two Device Types

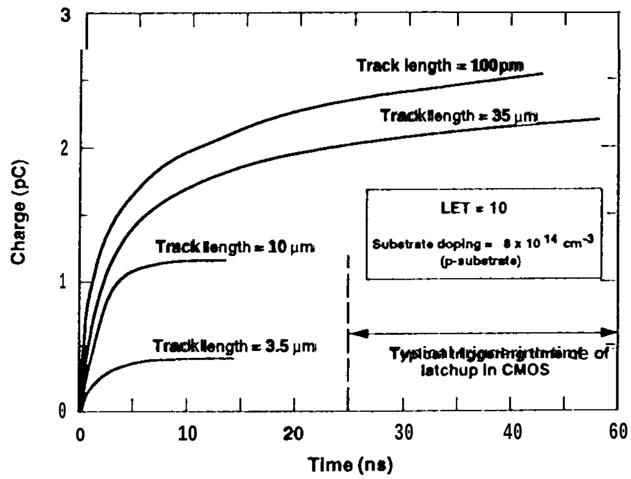

Figure 2. Effect of Track Length on Collected Charge (PISCES Calculations)

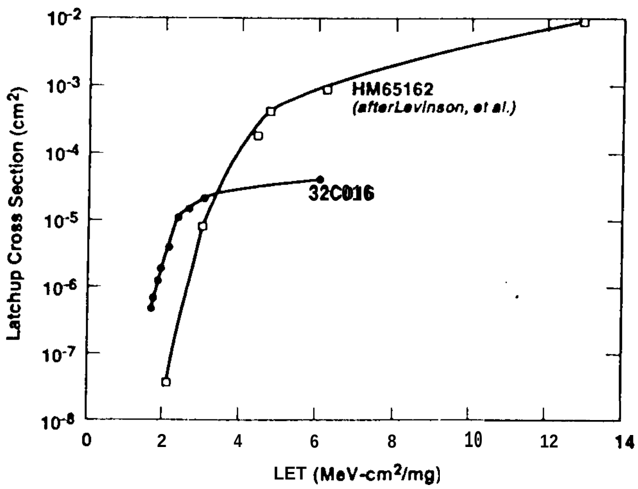

Figure 3. Heavy-Ion Latchup Cross Section for the Two Device Types

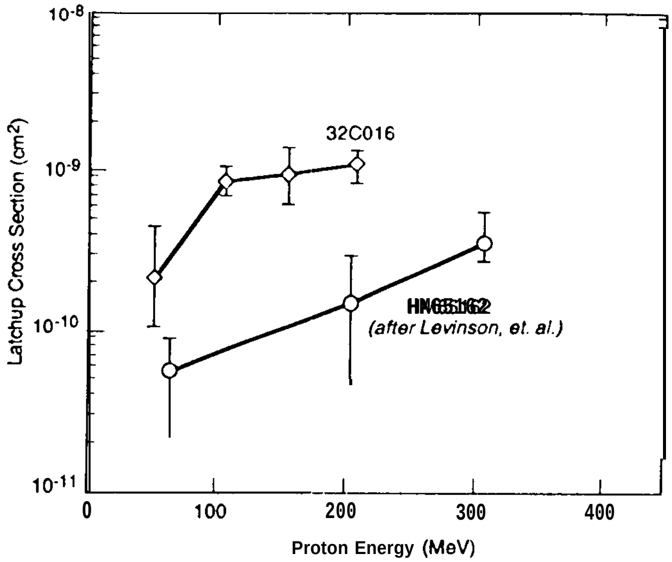

Figure 4. Dependence of Latchup Cross Section on Proton Energy

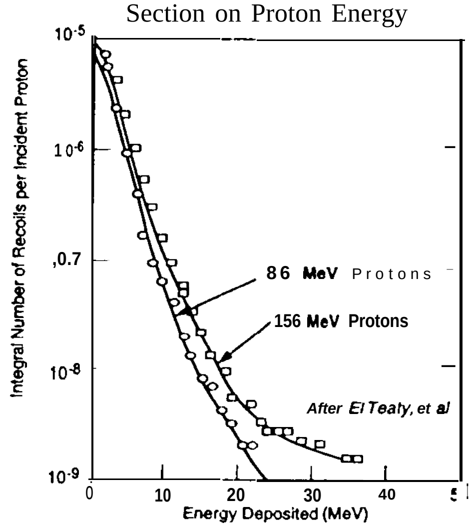

Figure 5. Recoil Energy Distribution for Two Proton Energies

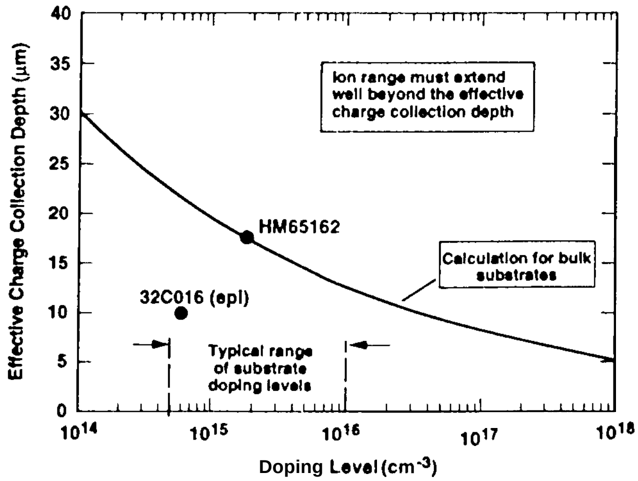

Figure 6. Effective Charge Collection Depth vs. Doping Density