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Latchup in Integrated Circuits from Energetic Protons[†]

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Abstract

Proton latchup was investigated for several CMOS integrated circuits, including a modern microprocessor. The proton latchup cross sections of these devices differed by more than two orders of magnitude. A modeling approach that takes differences in charge collection processes for long- and short-range particles into account was effective in comparing latchup cross sections in heavy-ion and proton environments, as well as explaining why the proton cross sections were so different among the device types.

I. 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 $\approx$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; many devices with upset thresholds between 5 and 7 MeV-cm^2/mg show no evidence of latchup when they are tested with protons. However, it is not obvious why this is the case, or whether this will hold for broader categories of devices.

Earlier attempts to model proton latchup are based on simple extensions of models for single-event upset [3-5]. These models are a useful starting point, but generally predict threshold conditions that are far too low, and are inconsistent with the dependence of cross section on proton energy that is observed for most devices. This paper discusses the mechanisms and processes for latchup, taking into account the differences between single-event upset and latchup to arrive at a more accurate picture of the proton latchup process. Several factors are important: (1) charge collection processes from the intermediate-range proton recoil atoms, which depend on doping levels and diffused layer thicknesses; (2) the dependence of the charge-collection depth on particle range and effective LET; (3) the very low cross sections that occur for proton latchup that cannot be directly related to saturation cross sections for ions with long range; and (4) fundamental dependencies of latchup on the specific geometry of the p- (or n-) well in CMOS processes.

Five different device types were considered in this work, all of which latched when they were irradiated with high-energy protons. They included bulk devices with n- and p-substrates, and two devices with epitaxial substrates. The wide range of technologies that were investigated provide insight into the effects of device fabrication differences and device scaling on sensitivity to latchup from protons. Spreading resistance measurements were made on samples of each device type in order to determine the underlying device structure because of its importance in charge generation and charge collection. The properties of all five device types are listed in Table 1. Proton and heavy-ion results for the HM65162 were taken from the work by Levinson, et al. [3], which characterized the latchup cross section of that device type very thoroughly for both heavy-ion and proton environments. New radiation test data was obtained for the other four device types. Heavy-ion testing emphasized the dependence of the latchup cross section on LET in the range of 2-15 MeV-cm^2/mg, which is the important region for comparing heavy ion and proton latchup.

II. LATCHUP MECHANISMS

A. Conditions for Latchup

The basic two-transistor model shown in Figure 1 for an n-well CMOS structure is the usual starting point for discussing latchup and latchup mechanisms. The properties of the parasitic bipolar transistors determine the conditions for latchup, and depend on layout and design rules for specific processes. Many elementary discussions start with the basic condition for regeneration in the two transistors, which is that the product of the gain of the two transistors must exceed one. This does not consider well and substrate resistances, which effectively short out the emitter-base regions of the two transistors until the internal currents are sufficiently high to maintain forward bias. The net result is

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Table 1. Properties of Devices Selected for the Proton Latchup Study

Device	Function	Manufacturer	Substrate Properties		
			Type	Doping Level (cm-3)	Epi-Thickness
NEC-4464	SRAM	NEC	n	7×10^{14}	- -
HM65162	SRAM	Harris	p	1.6×10^{15}	- -
32C016	SRAM	Harris	p (epi)	6×10^{14}	13 μm
LSI-64811	Processor	LSI Logic	p	2.5×10^{15}	- -
K-5	Processor	AMD	p (epi)	7×10^{14}	2.5 μm

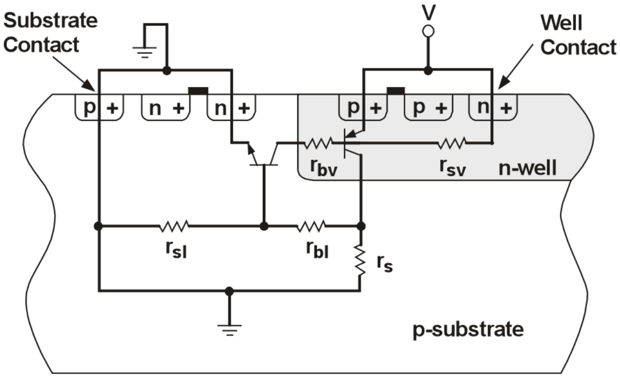

Figure 1. Basic two-transistor latchup model.

a much more stringent condition for latchup in real structures, along with an inherent dependence on isolation-well geometry and contact placement [6-10]. The extended geometry of the substrate region involved in latchup results in a relatively low resistance, even for substrates with low doping concentration. Consequently, equilibrium currents in the range of ≈ 50 mA to one ampere are typically required to sustain latchup.[†]

B. Latchup Triggering and Sustaining Conditions

Although much of the data in the device literature is concerned with latchup induced by surface currents, latchup from heavy ions is dominated by charge produced in the well-substrate junction. The very small charges produced by heavy particles are not sufficient to cause latchup directly. Latchup triggering involves several steps [7-9]:

(1) The small transient current from the ion strike must be sufficiently high to forward bias the vertical transistor (this requires a voltage drop of about 0.7 V in the well; the magnitude of the voltage drop depends on the location of the ion strike relative to the well contact and the anode);

(2) The *amplified* current from the vertical transistor must be high enough to turn on the lateral transistor; this requires a significant voltage drop in the substrate region; and

(3) The lateral transistor then turns on, producing a regenerative current in the isolation well that can sustain the conditions for maintaining forward-bias conditions on the vertical transistor.

In order to sustain latchup, equilibrium conditions in the device must be able to supply the required sustaining current after the initial triggering pulse from the heavy-ion strike decays. There is also a minimum voltage condition (holding voltage). Many CMOS structures are immune from latchup because the holding voltage -- which is basically determined by resistive drops in the well, substrate and metallization regions -- is above the available power supply voltage, even though the gain of the internal transistors is well above the minimum current sustaining conditions [6, 10,11].

The latchup process is inherently quite slow because the base regions of the parasitic transistors are relatively wide [11]. Typical triggering times for latchup are in the range of 20-50 ns, although this is expected to be somewhat lower for more advanced structures with smaller feature size. A triggering time of 20 ns is used as a reference for charge collection and triggering processes in this paper; that is the approximate time response of a parasitic latchup structure in

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[†] ”Microlatches” are sometimes reported in SEU testing that involve very small currents. This is inconsistent with the current requied to forward bias the substrate in conventional latchup, and may be caused by snapback or by logic conflicts from single-event upset.

CMOS with a feature size of 0.8 μm. As devices are scaled to smaller dimensions, the triggering time will be somewhat reduced, but 20 ns is a reasonable starting point for current device technologies. The relatively slow triggering time is of critical importance when charge collection processes are considered, increasing the contribution of diffused charge compared to SEU effects with faster initiation times.

C. Dependence of Latchup on Well Geometry

For single-event upset, elementary models often assume a constant charge collection volume for LET values near and somewhat above the threshold LET. This is a valid assumption for single-event upset in CMOS logic and flip-flops, where the triggering process is rapid, and charge collected at the drain of one of the two transistors is the essential threshold condition. However, the charge collection region that contributes to latchup is not constant, even near the threshold region.

Because the first step in latchup triggering requires the vertical transistor to be forward biased by the ohmic drop of the ion strike in the well region, the effective area involved in latchup depends on well geometry. For the rectangular well in Figure 2(a) with a 4:1 aspect ratio, only about 15% of the well area is sensitive to latchup at the threshold condition (minimum LET). The effective area involved in latchup triggering increases when the well is struck by ions with higher LET, because the increased charge allows the required 0.7 V drop in the well to occur in regions with lower distributed resistance, closer to the contact. For the "sparse contact" geometry of Figure 2(a), the result is that the effective area of the well that can trigger latchup will increase to about four times the initial cross section at the threshold as the LET increases. The relationship between area and LET near the LET threshold region is nearly linear for this case.

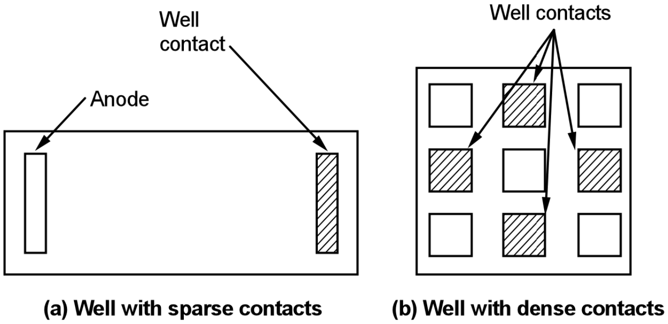


Figure 2. Well structures with different aspect ratios illustrating geometrical dependence on contact placement.

Many circuits use design rules that require substrate contacts to be placed at intervals within each well. Figure 2(b) shows an example for a square isolation well with dense contacts (this example uses much closer contact spacing than most circuits). In this case, the corner regions furthest from the contacts are the regions with highest latchup sensitivity (threshold condition). However, this area is less than 15% of the total well area,. As LET is increased, the cross section rises abruptly for this geometry until almost 80% of the well is involved, for an LET that is only about 50% higher than the minimum LET required in the corner regions.

These two cases show that the area of the isolation well that can trigger latchup will increase by factors of 4-5 as the LET is increased above the threshold condition. For dense contacts, the area will increase more abruptly, while for sparse contacts the increase will be gradual. Typical well geometries will probably lie between the two cases discussed above. There may also be more than one anode region if several MOS transistors are contained within the well. These factors cause the area involved in latchup to increase for ions with higher LET, and hence the relationship between cross section and LET may be quite complex for real circuits. However, the net result is a *non-constant* charge collection region for latchup, particularly for LET conditions slightly above the threshold condition. It is one of the reasons that the cross section for latchup increases over several orders of magnitude at low and intermediate LETs. Charge collection in the vertical direction also affects the charge collection volume, as discussed in the next section.

III. CHARGE COLLECTION

A. Proton Recoil Products

Several papers have discussed proton recoil products and proton cross sections [1,2,12-14]. Because the recoil products have short range, the number of interactions depends on the depth over which charge from the reaction recoils can be collected, as well as the effective area. As pointed out by Petersen, approximately one out of every 10^5 protons will cause a nuclear reaction in a thin slab, 4 μm thick [14]. For recoil products where the charge collected in the sensitive volume exceeds the threshold charge, the proton cross section will be approximately 10^5 smaller than the heavy-ion cross section. As discussed in references 13 and 14 it is also possible for proton reactions outside the charge collection volume to contribute to the total cross section, particularly for structures with small sensitive volumes. For most of the devices in the present study, the charge collection volume is much larger than the recoil track length, but that is not the case for the K-5 processor.

The distribution of recoil energies depends on proton energy. Figure 3 shows a representative example, after El Teleaty, et al. [13]. They used a surface-barrier detector, 2.5 μm thick, for their experiments. The number of recoil products decreases rapidly for higher recoil energies, and reaches a very low value near the kinematic limit (13.3% of the incident proton energy). If the experiment is repeated with higher incident proton energy, the number of protons with a *specifi*c recoil energy increases substantially compared to the case with lower incident energy. This will cause the volume for charge collection to increase with proton energy, unless it is physically limited (for example, by an epitaxial layer, or by isolation well contact placement)

There are also small numbers of particles with energy above the kinematic cutoff which are caused by rare proton events [14,15]. Their contribution is not considered in the present work. In most space applications, the contribution to the overall latchup cross section from heavy ions would be expected to be much larger that the contribution of the rare proton recoils.

The recoil products that are of most interest for proton latchup in space are particles with recoil energies ≈ 5-15 MeV. These particles have ranges of 2.5 to 3.5 µm. For short-range particles the collected charge is essentially dominated by the total energy of the particle, not LET. Consequently, total recoil energy is an effective way to compare the charge collected by recoil products with different energy in most latchup-sensitive structures.

B. Charge Collection from Long-Range Particles

Equilibrium conditions for charge collection depend on ion range. Two-dimensional simulations with PISCES were used to examine charge collection from particles with different ranges, using substrate doping levels that were within the range of the doping levels of the devices in this study. Figure 4 shows the results of these simulations for a p-substrate with a very shallow n-contact, subjected to a particle with LET = 10 MeV-cm^2/mg. A cylindrical geometry was used, with five-volt reverse bias, starting the particle track at the top of the structure. The track goes through the depletion region in all cases. The minority carrier lifetime (at low injection) was assumed to be 1 µs. The simulations show that in order to collect the maximum charge from a long-range particle with a specific LET, the range of the ion must extend well beyond effective charge collection depth. This is consistent with earlier charge collection studies relating charge collection to the depletion and funneling regions [16], although the simulations show that there is a more gradual transition between these limits. For lightly doped bulk substrates, typical of bulk CMOS, the particle range must be 35-40 µm even though the effective charge collection depth is only about 20 µm. The collected charge will be far lower when short-range particles are involved. The required range is less for n-substrates, because the funneling length is lower for holes than for electrons.

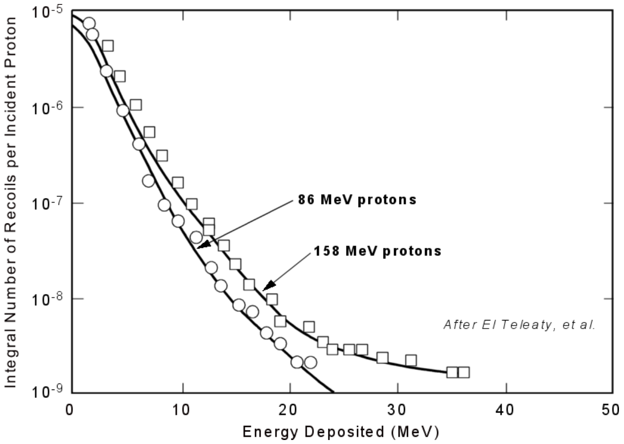


Figure 3. Recoil energy distribution from a 2.5 µm thick surface-barrier detector (after El Teleaty, et al. [13).

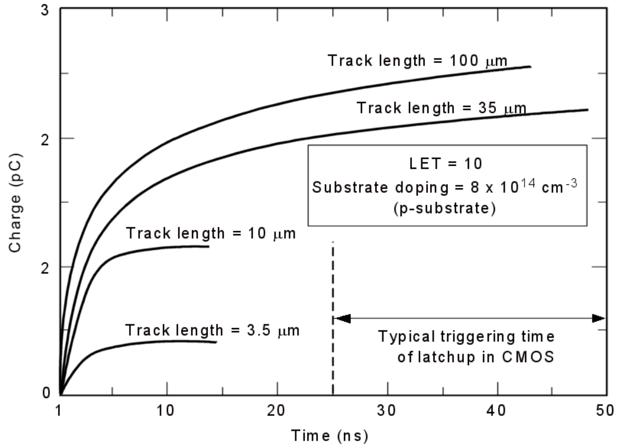


Figure 4. Results of PISCES simulations of collected charge for particles with different penetration depth.

The range required to collect most of the charge associated with the LET also depends on doping level, decreasing for higher doping concentrations. Figure 5 compares the results of calculations of range, using PISCES simulations, for p-substrates with different doping levels. The values corresponding to the four devices with p-substrates in the present study are shown for comparison.

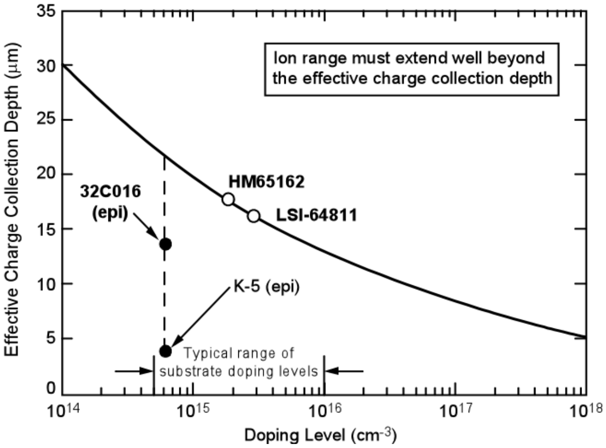


Figure 5. Effect of substrate doping on effective charge collection depth for p-substrates.

As shown by Dodd, et al., epitaxial substrates grown over a highly doped substrate do not necessarily cut off charge collection [17], particularly for charge collection times longer than 2 ns. Although the total collected charge in eptiaxial structures is reduced compared to the bulk case, a significant amount of charge can still be collected from the underlying highly doped region when long-range particles are involved. However, as discussed below, the highly doped substrate is effective at cutting off charge collection for short-range particles.

C. Charge Collection from Short-Range Particles

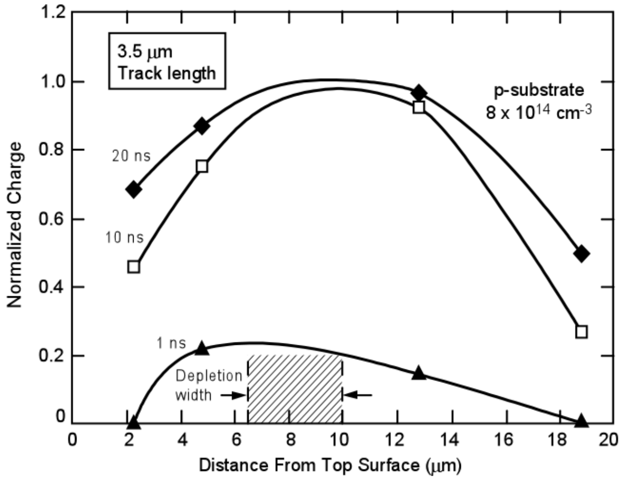
Proton recoils do not necessarily go through the depletion region, and one of the basic questions is how much charge is collected by typical recoil products in nearby regions of the p-n junction, because this determines the effective charge collection region for recoil products. A series of PISCES simulations was used to examine this question, using a well region 7 µm thick, with a doping level that is 20 times greater than the substrate doping. A 3.5 µm track length was used, with effective LET = 10 MeV-cm^2/mg. Figures 6(a) and 6(b) show the results of these simulations for two different substrate doping levels, normalized to the total ionization energy deposited by the particle. The charge collected at three different time intervals is shown. The points correspond to the center of the 3.5 µm particle track. At typical triggering times for latchup, a significant amount of charge is collected even for recoil products that are 10 µm beyond the edge of the depletion region, although the charge is somewhat lower than the maximum charge for particles that pass through the depletion region. This demonstrates that charge collection in the bulk region of the substrate well beyond the depletion region is important for short-range recoils, which has not been considered in previous latchup modeling efforts. The key points of these simulations are

(1) For a latchup condition with a fixed minimum charge threshold, the charge collection depth is not constant, but increases with the recoil product energy. This will cause the latchup cross section to be larger when the energy of the *incident* proton is higher because there are more recoil products with high proton energy. It also implies that models with constant charge collection volumes cannot satisfactorily explain the energy dependence of proton latchup for bulk substrates.

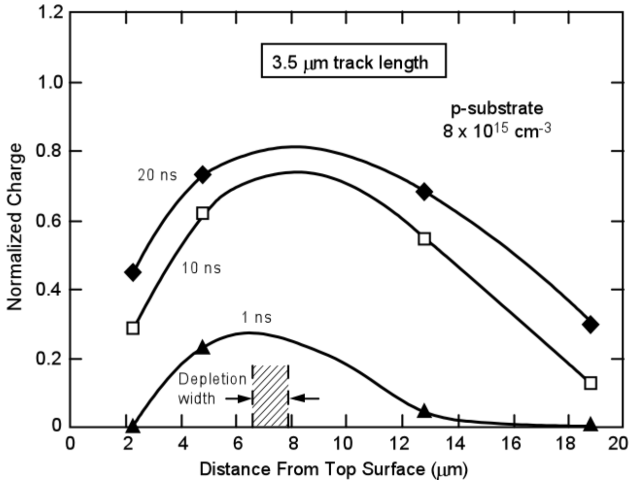
(2) For epitaxial substrates, the epitaxial thickness is an effective cutoff for charge collection with short-range particles, unlike the situation for particles with long range.

(3) The charge collection volume of devices with higher substrate doping due to charge collection depth will be less dependent on proton energy, which is important in considering the effects of device scaling on proton latchup. However, the lateral effects in the isolation well discussed in the previous subsection are still expected to be important for devices with higher substrate doping.

Examining Figure 6(a) in more detail, the charge collection depth for short-range particles more than doubles (using 20 ns as a triggering time) for recoil products with twice the minimum energy to initiate latchup. Because the number of recoil products increases with proton energy (see Figure 3), the charge collection depth will be higher as the proton energy increases in the region near the threshold. As discussed earlier, the effective area of the well involved in latchup triggering also increases with proton energy. The net effect depends on the product of these two factors. It explains why most proton latchup cross sections increase slowly, over several orders of magnitude, with increasing proton energy, as well as why models based on burst-



(a) Lightly doped substrate



(b) Moderately doped substrate

Figure 6. Charge collected from a particle with 3.5 µm track length placed at different vertical positions under a p-n junction.

generation rates with a constant charge collection volume do not work very well for latchup.

For conventional SEE effects where the response is rapid, the change in charge collection volume at higher recoil energies is less than for slower processes where charge diffusion can contribute. This is shown by the 1 ns charge collection results in Figure 6(b). Furthermore, the geometrical dependence on well geometry is absent for such effects. Thus, models that assume constant charge collection volume are more nearly correct for conventional SEE effects than for latchup.

IV. EXPERIMENTAL RESULTS

A. Experimental Procedure

Proton tests were done at the Indiana University cyclotron, using protons with energies up to 250 MeV. Heavy-ion tests were done at the Brookhaven National Laboratory Van de Graaff accelerator. A vacuum chamber was used for heavy-ion tests.

Latchup was determined by monitoring the power supply current during irradiation. After latchup was detected, the power supply was shut down within 100 ms to quench the latchup condition, and then reapplied. The latchup rate was kept low enough so that the "dead time" between successive latchup events was short compared to the irradiation time. The temperature of each device was monitored with a thermocouple to ensure that the device did not overheat, as well as to check that the temperature of the device in the "in-air" proton experiments was comparable to that of the heavy-ion tests, done in vacuum. This is important because latchup is affected by temperature [18]. Direct comparisons between proton and heavy-ion latchup would not be possible if the temperatures were significantly different.

Latchup results were obtained for 3-5 units of each device type. The total fluence was low enough to prevent interference from either total dose damaage or displacement damage. The results were very consistent for different units of a specific type, consistent with the mechanisms for latchup as well as for results on latchup in the literature.

Most of the devices that were tested had very low standby currents, and this made it easy to determine when large power supply current transients occurred. However, the K-5 processor is an important exception. The normal operating current of that device is nominally 1.4 A, a very high current. A special heat sink was used to keep the temperature below 55 ˚C during the heavy-ion tests that were done in vacuum. Because the current was initially so high, it was more difficult to develop unambiguous criteria for latchup in that device. The latchup events that were observed typically increased the current by more than 300 mA, but it is possible that some events with lower incremental current were not detected because of the high operating current of that device.

B. Substrate and Isolation Well Properties

Spreading resistance measurements were made on samples of each device type. Substrate doping levels and related properties of the five devices are listed in Table 1. The NEC4464 is the only device that is fabricated on an n-substrate. Because of the lower diffusion length, less charge is collected from the substrate region for that device than for p-substrate devices with equivalent doping levels. Spreading resistance measurements showed that the isolation well of the NEC4464 was much deeper -- 7 µm -- than that of the devices with p-substrates, which generally had well thicknesses of 2-3 µm. For that reason, a substantial fraction of the total collected charge is generated in the well region of the NEC4464, unlike the other device types.

The K-5 processor was fabricated on a shallow epitaxial substrate, 2.5 µm thick. The effective epitaxial thickness of that device is comparable to the range of recoil products from proton spallation reactions, which means that the recoil ions can no longer be considered as short-range particles relative to the charge collection distance for the K-5 processor.

C. Heavy-Ion Cross Sections

Heavy-ion tests were carried out at low LET values, using several different ions and incident angles to characterize the cross section in the regions that roughly correspond to the effective LET of proton recoil products with sufficient resolution. The K-5 processor was an exception; all tests of that device were done at normal incidence, because the test hardware interfered with the ion beam if angles were used. The range of the ions used exceeded 80 µm in all cases.

Most heavy-ion tests are not concerned with characterizing the region between 2 and 10 MeV-cm^2/mg with the resolution that is needed to make quantitative comparisons with proton latchup, and very few device types have been tested in this way. The reason that this is not done more often is simply that most applications are more concerned with higher LET values, near the iron threshold, and many systems simply reject devices with very low threshold LET for latchup from serious consideration.

Heavy-ion cross sections for two devices with p-substrates, the HM65162 and 32C016, are shown in Figure 7 (HM65162 results are from Reference 3). The 32C016 has a slightly lower threshold LET, and its cross section rises abruptly, saturating at ≈ 4 MeV-cm^2/mg. The cross section of the HM65162 increases more gradually with increasing LET. Its cross section is substantially above that of the 32C016 for LET > 3 MeV-cm^2/mg, and saturates at a value which is two orders of magnitude greater. This would lead one to expect that the proton latchup cross section would be much higher for the HM65162 than for the 32C016, However, as discussed in the next subsection, this is not the case; the reason for this apparent contradiction is explained in Section V.

Figure 8 shows heavy-ion cross sections for the other three devices (note that the NEC4464 has an n-substrate). All three devices show cross sections that increase by several orders of magnitude as the LET increases in the range 3-10 MeV-cm^2/mg. The NEC4464 and K-5 have similar cross sections at very low LET, and are among the most sensitive devices ever tested for heavy-ion latchup. The K-5 latched at an LET of 0.4 MeV-cm^2/mg. The NEC device has a significantly higher cross section at intermediate LET values, and one would expect that the proton cross section for this device would be higher than any of the other devices in the study, based on the low LET threshold and the very high cross section between 3 and 6 MeV/cm^2/mg.

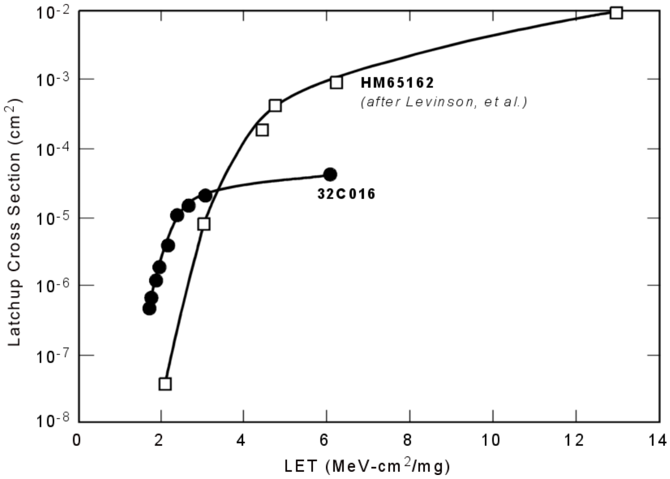


Figure 7. Heavy-ion latchup cross section for the HM65162 and 32C016. The 32C016 has an epi-substrate.

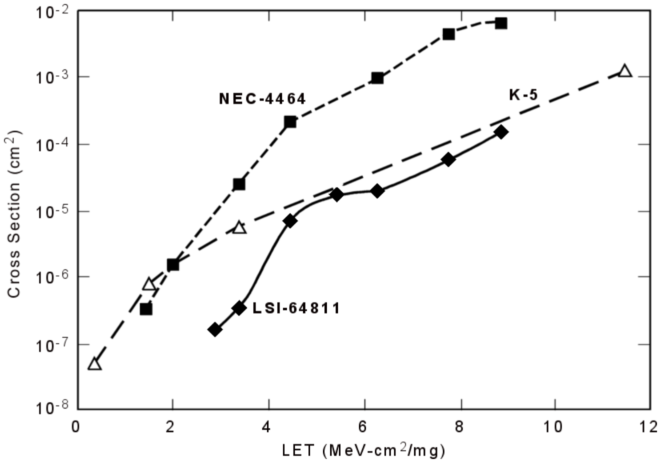


Figure 8. Heavy-ion latchup cross section for the other three device types.

To summarize the heavy-ion results, the cross sections of the five device types differ by more than two orders of magnitude for LET values in the 8-10 MeV-cm^2/mg region, which is the approximate threshold region where significant numbers of recoils are first produced by protons with incident energies of 100-200 MeV, although the proton recoils have much less range. The threshold LET for all five devices is low -- 0.8 to 3 MeV-cm^2/mg -- but it is not at all obvious how this relates to the recoils that are expected for latchup from protons. Four of the five device types have cross sections that increase gradually by about four orders of magnitude as the LET is increased from the threshold region to 8-10 MeV-cm^2/mg. The results in the next section will show that the proton cross sections are generally much lower than the rough order of magnitude predicted by dividing the cross section in the 8-10 MeV-cm^2/mg region by the approximate number of proton recoil events (10^5). This implies that for most devices proton latchup must be dominated by regions well below that region. It also implies that one cannot use arbitrary definitions of threshold cross sections (such as "10% of the saturation values") to develop effective models for proton latchup.

D. Proton Cross Sections

Although the HM65162 exhibited a very high cross section at intermediate LET values when it was tested with heavy ions, the proton cross section of that device was so low that it was difficult to measure [3]. Figure 9 shows proton latchup cross sections for the HM65162 and 32C016; compare these results with the heavy-ion cross sections for the same two device types in Figure 7. In spite of the fact that the HM65162 heavy-ion cross section is much higher (except for LET values < 3 MeV-cm^2/mg), the proton latchup cross section of the HM65162 remains much lower than that of the 32C016, even at very high proton energies. Furthermore, the two parts show very different responses. The 32C016 cross section increases rapidly at low proton energies, and then saturates, consistent with the concept of a fixed charge collection volume (recall that this device has an epitaxial layer with a depth of about 13 μm). On the other hand, the cross section of the HM65162 increases steadily as the energy increases, consistent with the concept of a continually increasing charge collection region.

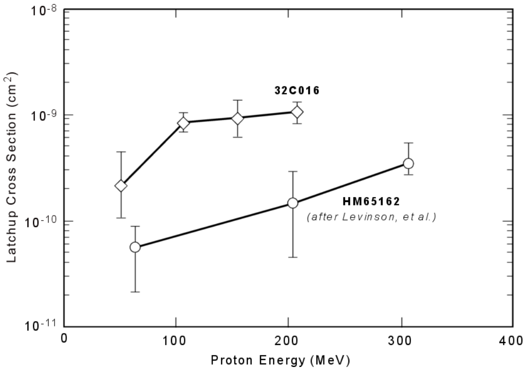


Figure 9. Proton latchup cross sections of the HM65162 and 32C016 devices.

The proton cross section of the NEC4464 was also very low, even though that device had a high cross section at intermediate LET values. Proton test results for the NEC4464 are shown in Figure 10. The cross section of that device increases only slightly with proton energy, in contrast to the cross section of the HM65162. The proton cross section of the LSI-64811 was very low, near the practical detection limit for incident energies of 200 MeV; the measured cross section was 1.7 x 10^{-11} cm^2. The device would not latch when it was irradiated with 80 MeV protons. Proton tests of the K-5 processor were done only at 200 MeV. The K-5 had the highest cross section of any of the devices that were tested, 6.7 x 10^{-9} cm^2.

The proton latchup cross sections of the five device types differ by about a factor 300, which is a very large difference, but it is not clear how this is related to device structure or the sensitivity of these devices to latchup from heavy ions. In some cases devices with very low threshold LET values and high cross sections have much lower proton latchup cross sections compared with other device types that have lower cross sections and higher LET threshold for heavy-ion latchup. This would suggest that there is not much hope in relating latchup in heavy-ion and proton environments. However, the modeling approach in the next section explains these differences, based primarily on a more thorough analysis of charge collection for the different device types.

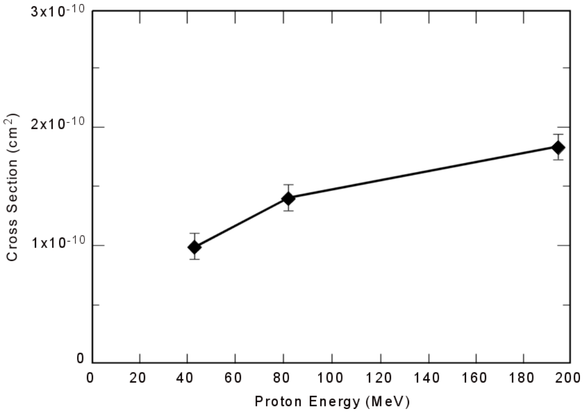


Figure 10. Proton latchup cross section of the NEC4464.

V. DISCUSSION

A. Threshold Conditions

The differences in charge collection for long-range heavy ions and short-range proton recoil products provide a starting point for comparing latchup in the two environments. The PISCES simulations show that the effective charge collection depth is quite different for the two cases. This, coupled with the fact that the cross sections for proton latchup are inconsistent with the relative values of heavy ion cross sections and threshold LET suggests that only part of the region involved in heavy-ion latchup is effectively involved in proton latchup. If one can relate the threshold conditions, then it should be possible to get a better understanding of why the proton cross sections vary over such a large range.

One way to approach this is to compare the charge collected by the well-substrate junction when it irradiated with heavy ions to the charge collected by a short-range proton recoil product in the same structure. Let us define a recoil product with an energy of 10 MeV as a measure of comparison; Figure 3 shows that there are a significant number of particles with that energy range for incident protons with energies of 100 MeV and above. Let us further assume that all of the recoil energy is lost via ionization processes in the semiconductor, with 100% charge collection; this is consistent with the results of the PISCES calculations in Figure 6 for time periods of 20 ns. The charge produced by the recoil is then 0.46 pC, and this value will be used in subsequent comparisons.

The effective charge collection depth in Figure 5 can be used to determine the heavy-ion LET that corresponds to the 0.46 pC produced by the proton recoil. Note, however, that Figure 5 applies only to p-substrates; additional PISCES simulations showed that the effective charge collection depth in n-substrates is lower by a factor of 1.6 because of the difference in diffusion length.

Even though the total cross section for either heavy ions or protons depends on the well geometry, the measured heavy-ion cross section is essentially an empirical determination of the effective area under equivalent collected charge conditions. Thus, the heavy-ion cross section at the LET corresponding to 0.46 pC corresponds to the well area involved in proton latchup for recoils that generate the same value of charge. The net proton cross section also depends on the depth over which proton recoils contribute near maximum charge. These two factors can be combined to calculate the proton cross section from heavy-ion test results.

The approach is summarized below. It assumes that experimental heavy-ion cross section results are available, as well as the doping levels and thickesses of the substrate and isolation well:

(a) Determine the effective charge collection depth for long range particles (see the PISCES results in Figure 5).

(b) Calculate the heavy-ion LET value corresponding to 0.46 pC from the charge collection depth and heavy-ion test data. This determines the effective cutoff point for latchup from proton recoils; the region of the heavy-ion cross section above that threshold LET value requires charge above the 0.46 pC value that we are using as a benchmark.

(c) Divide the cross section corresponding to the equivalent LET in the previous step by the number of proton events that are expected in the charge collection depth corresponding to short-range particles (≈ 2.5 x 10^4 times the effective charge collection depth) to arrive at a final value for the proton cross section.

The results of these calculations are shown in Table 2. Measured proton cross sections are shown for comparison (energy = 200 MeV). The agreement is generally within a factor of two (slightly worse for the HM65162), even though the raw proton cross sections differed by a factor of about 300 among the various device types. This holds for a wide range of devices, two of which were fabricated on epitaxial substrates. The close agreement between this model and the experimental proton results shows that the wide differences between proton and heavy-ion latchup cross sections are indeed directly related to the fundamental charge collection process for long- and short-range particles.

B. Advanced Devices and Scaling

The K-5 processor is distinctly different from the other four device types, with a very shallow epitaxial structure. Reasonable agreement was obtained between heavy-ion cross section results and the proton cross section at 200 MeV for that device as well, even though the recoil products no longer have short range for that case. The threshold condition estimated for equivalent charge for that device corresponded to 12 MeV-cm^2/mg, suggesting that for more advanced devices with shallow structures latchup from protons will occur for device with threshold LET near the kinematic threshold. It also raises the possibility that proton latchup may be a more severe issue for advanced devices.

We were surprised at how readily latchup occurred for the K-5 processor, given the fact that the part is fabricated on an extremely shallow epitaxial substrate. Tests by our laboratory on several other advanced devices with similar substrate technology have generally shown that such devices are relatively immune to latchup, even when very high LET ions are used. We intend to examine this device in more detail in the future to determine what factors in the well design and layout make the part so sensitive to latchup. This will require stripping away the metallization, but it is a fascinating result that was not expected from basic considerations of latchup sensitivity.

C. Other Modeling Considerations

Proton Energy Dependence

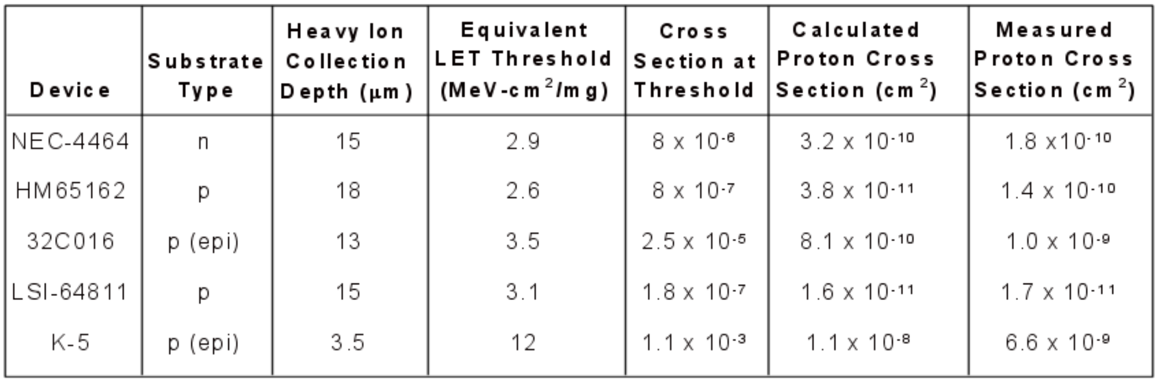
For most devices, the dependence of proton latchup cross section on proton energy is rather weak. The strongest dependence occurred for the HM65162 and, within the limits of our test results, the LSI-64811 (the cross section for the latter device was near the practical detectable limit of ≈ 10^{-11} cm^2). In both cases the proton cross sections are very low relative to the heavy-ion cross section, which may make the device more sensitive to proton energy because the relative number of recoils involved in latchup are lower than for the other device types.

Although the 32C016 uses a very thick epitaxial region compared to more modern devices, the cross section of that device increased much more abruptly than for devices without epitaxial substrates. This is consistent with the PISCES simulation results that show a nearly constant charge collection depth for epitaxial substrates. The well area and contact geometry are still important, but the abrupt increase and saturation of the cross section of that device may indicate that the isolation well uses many contacts with regular spacing, reducing the importance of the goemetrical factor associated with the well layout.

Angle Effects

Although no irradiations were done using protons at other than normal incidence, Reed, et al. have pointed out that spallation products are not isotropic, and that the cross section should be greater for cases where experiments are done at angle than for normal incidence [20]. For p-substrate devices, our charge collection simulations show that most of the charge is collected from the substrate region, not the

Table 2. Results of Model Calculations Relating Heavy-Ion and Proton Latchup



Device	Substrate Type	Heavy Ion Collection Depth (μm)	Equivalent LET Threshold (MeV-cm^2/mg)	Cross Section at Threshold	Calculated Proton Cross Section (cm^2)	Measured Proton Cross Section (cm^2)
NEC-4464	n	15	2.9	8×10^{-6}	3.2×10^{-10}	1.8×10^{-10}
HM65162	p	18	2.6	8×10^{-7}	3.8×10^{-11}	1.4×10^{-10}
32C016	p (epi)	13	3.5	2.5×10^{-5}	8.1×10^{-10}	1.0×10^{-9}
LSI-64811	p	15	3.1	1.8×10^{-7}	1.6×10^{-11}	1.7×10^{-11}
K-5	p (epi)	3.5	12	1.1×10^{-3}	1.1×10^{-8}	6.6×10^{-9}

isolation well, and for these cases the dependence of the latchup cross section on incident angle would be expected to be less significant because there is sufficient “dead” silicon above the region where most of the charge is collected so that the total number of recoils collected within the sensitive region is only weakly dependent on angle.

For n-substrates, our PISCES simulations show that charge generated within the well is far more significant than for devices with p-substrates. This suggests that angle effects will be easier to observe, and more important from a testing standpoint, for devices with n-substrates, particularly those with relatively thick p-wells. A significant angle effect was observed by Adams, et al. for proton tests of the NEC4464 [21]. The well region of that device is much thicker than most CMOS devices (7 μm). Thus, the NEC4464 is expected to have a more extreme dependence on angle than most other device types. However, Levinson, et al. showed a very weak angle effect for the HM65162, which has an n-substrate [22]. Both results are consistent with our charge collection modeling.

More work needs to be done to investigate angle effects, particularly for devices with shallow structures. However, our modeling results suggest that the effects will be small, less than a factor of two, for highly scaled devices on p-substrates.

Charge Collection Modeling

Because latchup is a relatively slow process, the detailed response of the collected charge at very short times (< 1 ns) is of little importance. Consequently, the interpretation of charge collection results is not very dependent on mobility models, which primarily affect the response at short times [23]. This may not hold for more heavily doped material, but nearly all CMOS integrated circuits use lightly doped substrates. Note that the doping level of the K-5 processor, a very modern device, is not much different from the doping levels of devices that were designed many years earlier.

Similarly, because the PISCES results for simple structures discussed earlier show that nearly all of the deposited charge is collected, even for short-range recoils that are 10 μm away from the depletion region, it appears unlikely that 3-D simulations would produce significant differences from the 2-D results for charge collection. Three dimensional simulation is clearly necessary to simulate latchup in circuit structures [9], but it does not appear to be essential to determine the depth over which significant fractions of deposited charge can be collected from short-range particles.

The key point of the charge collection modeling is that charge collection occurs over much deeper regions of the substrate than assumed by many of the earlier studies on proton latchup [3-5, 21, 22]. The earlier work did not attempt to do detailed modeling of charge collection, simply assuming that because the recoil products have short range, the charge collection volume would have comparable dimensions. The charge collection simulations in the present work, along with the close agreement of calculated proton cross sections with a model based on more realistic determination of charge-collection depth, support the conclusion that the extended charge collection region is indeed effective for latchup. Note however that the charge collection depth for phenomena with faster response times may be more shallow, with a stronger dependence on doping concentration than for latchup (see Figure 6).

VI. CONCLUSIONS

This paper has discussed proton latchup in several device types with different underlying structures. The proton latchup cross sections of these devices differ by more than two orders of magnitude, and do not correlate with differences in either the threshold LET or the cross section at intermediate LET when the same device types are irradiated with heavy ions. These differences can be explained by fundamental differences in the charge collection process of long-range heavy ions and short-range proton recoils in the different device types.

The basic modeling approach developed in the paper provides a more accurate way to estimate proton cross sections from heavy-ion test results than previous models that have assumed constant charge collection regions, and have also underestimated the charge collection depth. The model was applied to devices with markedly different construction and topology. It predicted proton cross sections that were generally within a factor of two of the experimental values.

The results of the study show that substrate properties play a major role in latchup sensitivity. Substrate resistivity is not always well controlled in CMOS processes, and monitoring substrate technology may be essential in bounding the latchup sensitivity of commercial processes.

The high proton latchup cross section observed for the K-5 processor shows that even very advanced devices with shallow epitaxial substrates can be very sensitive to latchup from protons. The charge collection model, which also worked for that device, suggests that the effective LET cutoff for advanced devices may be near the kinematic limit, unlike older devices which are typically only sensitive to proton latchup if their threshold LET for heavy-ion latchup is in the range of 2-3 MeV-cm^2/mg.

The inherent dependence of latchup on device geometry makes it difficult to develop models for latchup in real integrated circuits, even when fundamental interactions and geometrical factors are well understood. The presence of many possible latchup paths with different threshold conditions and saturation cross sections further complicates the latchup problem. Additional work needs to be done on advanced devices to improve our understanding of how variations in processing and device technology will affect latchup, as well as whether latchup detection and circumvention approaches are effective, and how the high currents produced during latchup affect reliability.

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