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Single-Event Upset Effects in Optocouplers†

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Abstract

Single-event upset is investigated for optocouplers using heavy ions. The threshold LET for optocouplers with internal high-gain amplifiers is very low, causing output transients to occur even when the optocouplers are irradiated with short-range alpha particles. Although previous work with high-energy protons showed that transients were caused by charge collected in the large-area photodetector, transients generated in the high-gain amplifier make a significant contribution to the total cross section when optocouplers are irradiated with heavy ions.

The transient pulse width increases with LET, exceeding 400 ns for long-range particles above 7 MeV-cm^2/mg. This is about an order of magnitude greater than the pulse width that occurs when they are irradiated with protons. The ion range must exceed 50 µm to characterize the cross section and pulse width in these devices.

I. INTRODUCTION

Transients induced in optocouplers by protons were identified as the cause of anomalies in the Hubble Space Telescope, as reported by LaBel, et al. [1]. In laboratory tests with protons, they observed transients with durations of 20-60 ns in high-speed optocouplers. They attributed the results to transient currents from proton recoil products collected in the large-area photodetector of the optocoupler.

The present paper investigates the effects of heavy ions on optocouplers. Mechanisms for the response are investigated, along with the dependence of the amplitude and pulse width on LET. Charge collection is investigated for long and short-range particles using the PISCES device analysis program.

Three types of optocouplers were studied: the 6N134 which is essentially the same as the HCPL-5631 used in the Hubble Space Telescope; the HCPL5203, which uses an input amplifier with lower minimum LED drive current compared to the 6N134/5631 series of devices; and the 6N140, which uses only a simple (Darlington) transistor amplifier. All of the HP devices use a GaAsP LED with a wavelength of 700 nm. Circuit diagrams of the two basic types of HP devices are shown in Figure 1. They are fabricated in a sandwich configuration with the LEDs mounted on a separate substrate above the silicon die, providing more consistent optical coupling than laterally coupled optocouplers.

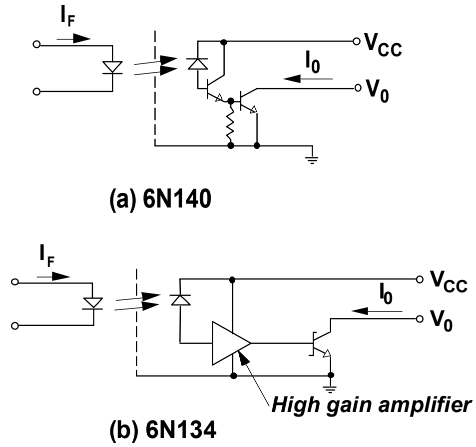

Figure 1. Circuit diagrams of the two basic types of optocouplers from Hewlett-Packard.

For heavy-ion tests, the LED assembly was removed from all three structures in order to allow heavy ions to penetrate the silicon subassembly.†† Optical coupling material that remained on the silicon die after partial disassembly was removed with a solvent before testing. In addition to the three HP devices, special charge collection measurements were done on 4N49 optocouplers, which provide direct access to all three leads of the input phototransistor. The 4N49, manufactured by Optek, uses lateral rather than vertical coupling between the LED and phototransistor [2], with a longer wavelength LED (890 nm). Table 1 summarizes the characteristics of the devices that were tested.

All three Hewlett-Packard devices have photodiodes with nearly identical area ($\approx 1.3 \times 10^{-3}$ cm^2). For the 6N140, the diode occupies most of the chip area. For the 5203 and 6N134, the combined areas of the amplifier and output driver are slightly larger than that of the photodiode.

Most of the single-event upset tests on the optocouplers were done at the Brookhaven National Laboratory Van de Graaff. During these tests, each transient waveform was captured with a digital oscilloscope, providing a way to analyze each waveform in detail and also assuring that the cross section was not influenced by noise or short-duration transients. The flux was less than 5000 ions/(cm^2-sec) in order to minimize interference from multiple ion strikes. Five volts was applied to each of the HP devices during testing, using a 2 mA load condition (circuit details are described in the Appendix).

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††With the LED assembly removed, it is only possible to test the device in the "off" state. This is normally the most sensitive condition unless the LED is driven at very low currents.

Table 1
Properties of the Optocouplers

Type	Wavelength	Input LED Current	Internal Circuit	Manufacturer
5203	700 nm (GaAsP)	0.5 mA	High-gain amplifier	HP
6N134	700 nm (GaAsP)	3 mA	High-gain amplifier	HP
6N140	700 nm (GaAsP)	10 mA	Darlington transistor	HP
4N49	890 nm (AlGaAs)	1 mA	Single transistor	Optek

A limited set of tests was also done at the Texas A&M cyclotron, including charge collection measurements of the 4N49. Ions from the latter facility have considerably greater range than ions at BNL. Tests were also done using laboratory alpha particle sources. Table 2 lists the ion types that were used in the heavy-ion experiments. The last three ions are available at Texas A & M, and have considerably longer range than ions with similar LETs at Brookhaven.

Table 2
Properties of the Various Ions Used

Ion	LET (MeV-cm^2/mg)	Energy (MeV)	Range (µm)
Li	0.37	57	389
C	1.4	110	179
F	3.2	150	116
Cl	11.5	210	63
Ti	18.8	228	48
Ni	26.6	266	42
Ar	7.7	600	229
Kr	25.1	1285	153
Xe	43.7	1960	128

II. Test Results

A. Results for Heavy Ions

Both amplitude and pulse width have to be considered when describing transients from linear circuits. The two optocouplers with internal amplifiers were extremely sensitive to heavy ions. The threshold LET -- the LET at which transients first occurred -- was approximately 0.3 MeV-cm^2/mg, an extremely low value.

At low LET values, a single pulse width occurred in the majority of cases, but there were also a small number of transients with shorter duration. Figure 2 shows how distributions of pulse widths change for different LETs. The majority of pulses occurred within a very narrow range of values, with a slight "tail" in the direction of lower pulse widths. This is consistent with charge collection from the large area photodiode; the "tail" is expected because charge can be collected by diffusion when ions strike regions just beyond the periphery of the diode, with less charge compared to ions that strike the physical region of the diode and pass through the depletion region. However, even at 2.1 MeV-cm^2/mg there are a small number of pulses with shorter pulse width (about 70 ns), which do not appear consistent with a diffusion "tail" from the dominant distribution because of the gap between the 70 ns and 130 ns peaks. At higher LET values, the "tail" associated with the dominant response increases, along with the relative number of pulses from the second distribution (shorter pulse widths). This trend continues as the LET increases. The pulse width histograms imply that the diode contribution only dominates the response at low LET, and that a second mechanism becomes increasingly important at higher LET.

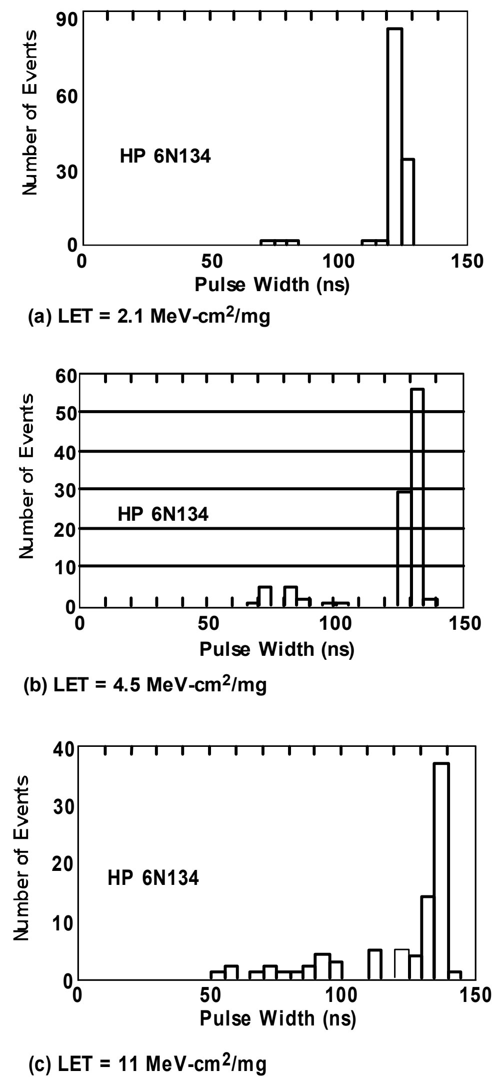


Figure 2. Pulse width distributions at various LET values

Figure 3 shows the dependence of pulse width on linear energy transfer for the 6N134. Both mean values and the dominant pulse width (assumed to be due to ions striking the photodiode region) are shown. Initially the mean pulse width is very nearly the same as that of the dominant pulse width (indicating that relatively few transients of shorter duration occur), but as the LET increases there are relatively more pulses with shorter duration. At low LET, the pulse width increases with LET to about 125 ns, reaching that pulse width at approximately 1 MeV-cm^2/mg. It continues at about that same value up to an LET of about 12 MeV-cm^2/mg. At that point the character of the response changes. Some pulses have much longer pulse width, and there are also relatively larger numbers of narrow pulses. Thus, it is no longer possible to select a single dominant pulse width from the distribution of pulses. This is the reason for the change in slope for LETs above 12 MeV-cm^2/mg. This appears to be caused by the superposition of the photodiode response with the response of the amplifier.

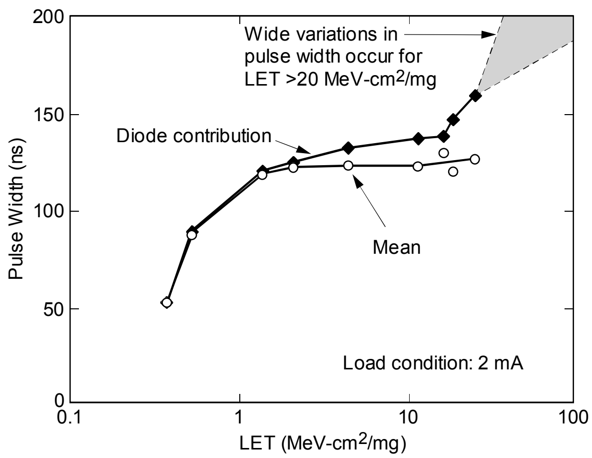
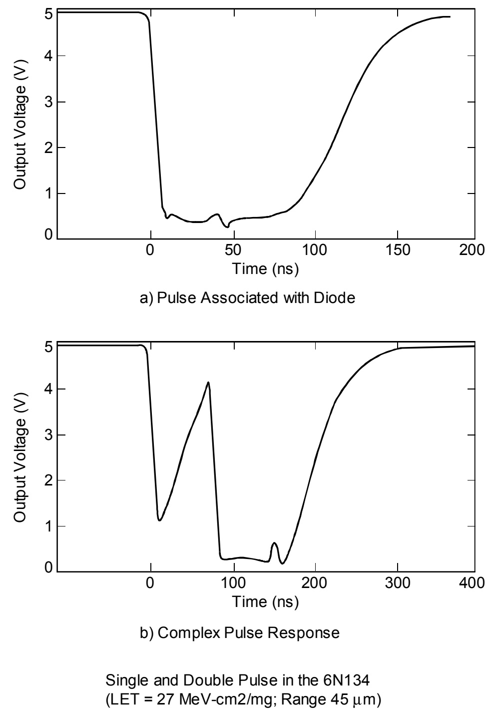


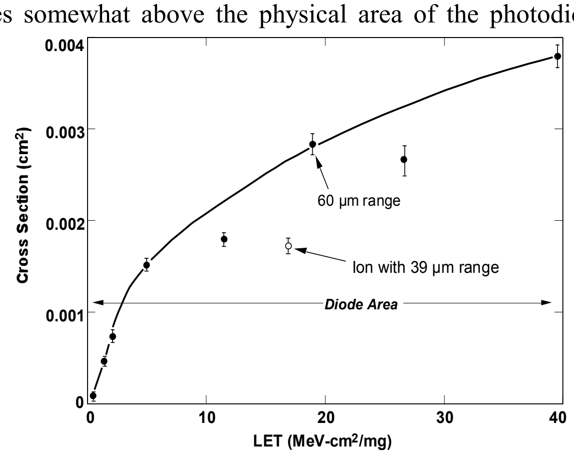
Figure 3. Dependence of pulse width on LET for the HP5203 optocoupler

When irradiations were done at angles a "double pulse" sometimes occurred, a narrow pulse and a wider pulse that occurred slightly afterwards. Figure 4 shows examples of the two types of pulses that were observed. The LET was 27 MeV-cm^2/mg, the range was 48 µm, and the irradiation was done at a 45º incident angle. The wider of the two pulses appears to be a superposition of the pulse width that was attributed to the photodiode during irradiations at normal incidence along with a second pulse. The occasional "wide" pulse width was simply a filling in of the two responses due to diffused charge from the photodiode (note the delayed response of the secondary pulse in Figure 4). In limited tests at Texas A&M, pulse widths up to 400 ns were occasionally observed at an LET of 7 MeV-cm^2/mg. The range of the ions in those tests exceeded 200 µm, which extends the charge column deep into the substrate.

The dependence of cross section on LET is shown in Figures 5 and 6 for the two optocouplers with high-gain internal amplifiers. Error bars reflect counting statistics. (The lines in the figures are intended to guide the eye, but reflect the



expectation that particles with lower range will likely result in a lower cross section). The threshold LET is very low, approximately 0.3 MeV-cm^2/mg (note that the cross section increases steeply in this region). The cross section rises to values somewhat above the physical area of the photodiode,



even though the pulse width distributions show that most pulses have the single value associated with the diode. This indicates that lateral charge diffusion makes a significant contribution to the cross section.

Figure 4. Example of double pulse for LET_{eff}= 27 MeV-cm^2/mg (45 ° incident angle). Note the different time scale for the two traces

Figure 5. Cross section vs. LET for the HP5203 optocoupler

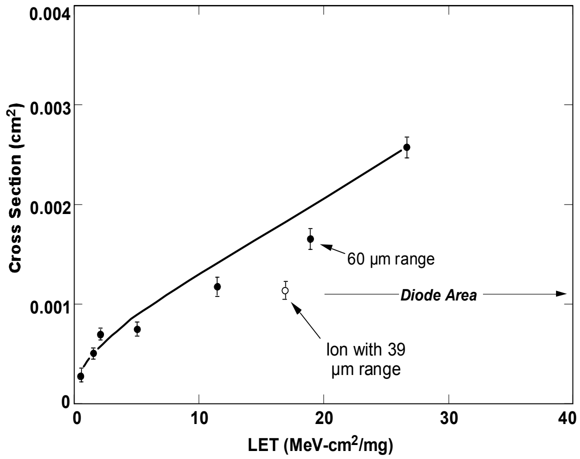


Figure 6. Cross section vs. LET for the HP6N134 optocoupler

This is further corroborated by examining the two data points with LET values of 16-18 MeV-cm^2/mg. The range of the ion with the open symbol was 39 µm; the other had a range of 60 µm. The longer range ion has a cross section that is about 30% greater than that of the shorter range ion, even though the LET is nearly the same. Note also that the cross section of the 39 µm ion is slightly lower than the pulse width that occurs at 11 MeV-cm^2/mg (the range of that ion was 63 µm. The difference in cross section for ions with relatively long ranges provides evidence that charge collection occurs over a very deep region of the device, well beyond that observed for more conventional devices. Although diffusion also occurs in the lateral direction, the large diameter of the photodiode (about 400 µm) reduces the relative importance of lateral diffusion compared to diffusion in the vertical direction.

The response of optocouplers without complex integrated amplifiers is more straightforward. The 6N140 has only a basic transistor amplification stage (see Figure 1). The threshold LET was about 11 MeV-cm^2/mg, as shown in the cross section results of Figure 7. The threshold LET was more than an order of magnitude higher than that of the more complex optocouplers that contain a high-gain amplifier. The pulse width distribution of the 6N140 was very narrow, consistent with expectations for a basic optocoupler where there is no high-gain amplifier. Thus, the simple transistor amplifier of the 6N140 does not contribute to the cross section. The amplitude of the transient pulses of the 6N140 was 100-800 mV, less than 20% of the power supply (logic) level with a 2 mA load condition. The maximum cross section observed for the 6N140 is much smaller than the photodiode area, and depends on load conditions. With a load current of 2 mA, the charge induced by ions with LET up to 40 MeV-cm^2/mg is barely large enough to begin to turn on the device.

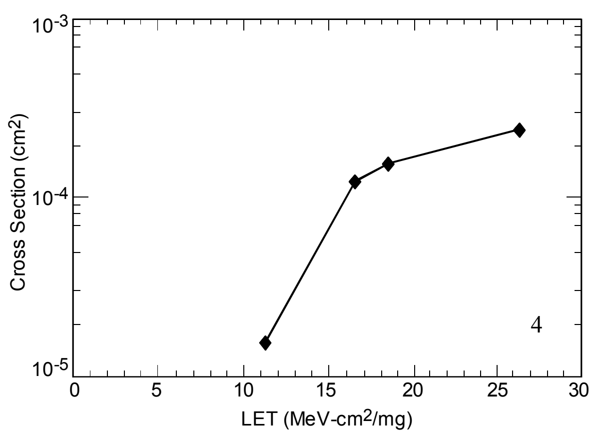


Figure 7. Cross section vs. LET for the 6N140 optocoupler

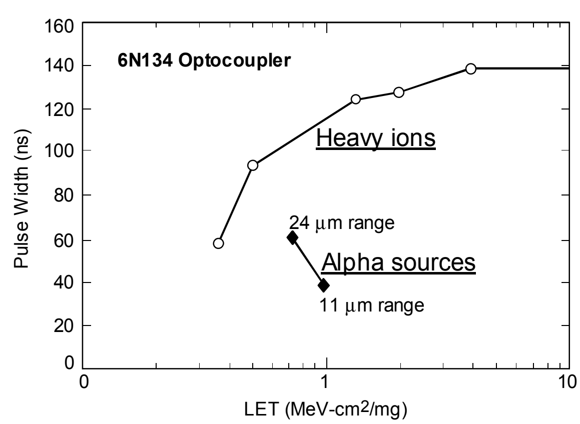
B. Results on Partially Shielded Units

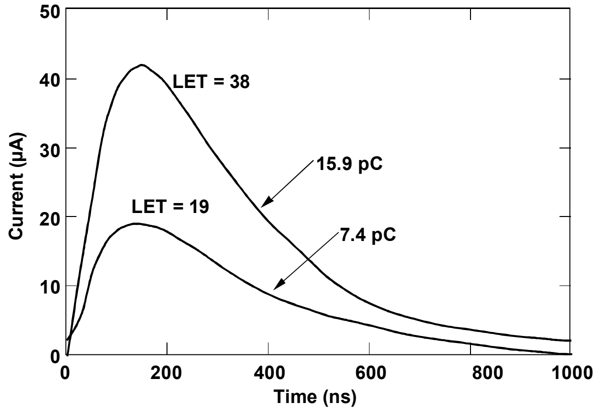
In order to provide more direct evidence that the dominant pulse width in the pulse distributions was caused by charge collected in the photodiode, a series of tests was done with a shield that prevented ions from striking regions of the circuit beyond the photodiode. This allowed the contributions of the photodiode and amplifier to be identified by comparing shielded and unshielded results. Pulses with narrow pulse width (the region with 70 ns pulses in Figure 2) no longer occurred when the shield was in place. Only pulses with 125-130 ns pulse width occurred (with an LET of 3-27 MeV-cm^2/mg). The cross section was slightly lower compared to the unshielded results, due to partial occlusion of the photodiode when the shield was in place.

C. Results with Laboratory Alpha Sources

Measurements were made with two laboratory sources, ^{148}Gd, which produces 3.2 MeV alpha particles, and ^{208}Po, which produces 5.1 MeV alpha particles. At the surface, the LET of the Gd source is nearly 1 MeV-cm^2/mg , while the LET of the higher energy Po source is 0.7 MeV-cm^2/mg. The range of these particles are 11 µm for the 3.2 MeV Gd, and 24 µm for the 5.1 MeV Po. Figure 8 compares the pulse width of the 6N134 when it was irradiated with the two alpha particle sources with the results for long-range ions (during tests with the accelerator). For the alpha sources, the pulse width *decreases* with increasing LET; the pulse width for both sources is also substantially below that obtained with the long-range ions. The pulse width with the Po source is about 60% greater than that with the Gd source, nearly identical to the ratio of the energy of the two alpha particles. This shows that it is the energy (essentially deposited charge) of the alpha particle, not the LET in the first few microns that determines the device response. This provides further evidence that charge collection occurs over an extended distance in these structures.

Figure 8. Comparison of the pulse width of the 6N134 when it is irradiated with long-range ions and short-range alpha particles. The cross section decreases with LET for the alpha particles, and the ratio of the pulse width is nearly identical to the ratio of the alpha particle energies.





III. CHARGE COLLECTION

The photocurrent produced by heavy ions was measured with the 4N49 optocoupler, which provides direct connection to all three leads of the phototransistor (circuit details are discussed in the Appendix). It was not possible to do this type of measurement on the 6N140 because the base connection is not accessible. These results are shown in Figure 9. Note the very long duration of the transient response. The effective charge collection depth of this device is 44 µm (obtained by comparing the total collected charge with the charge density of the ion used in the experiment). Most of the charge is collected during the first 200-500 ns. As the LET increases, the time at which the current falls below a specific threshold condition (such as the threshold for a high-gain amplifier) extends out in time, consistent with the response of the more complex optocouplers. Thus, the gradual increase in the width of the dominant response, associated with the photodiode component of the cross section, is consistent with charge collection measurements which show that charge is collected over extended time periods.

Figure 9. Charge collection measurements of the phototransistor in the 4N49 optocoupler.

Spreading resistance measurements (made with an automated probe on a sample that was lapped at a shallow angle) were used to determine the doping concentration and underlying structure of the optocouplers. Figure 10 shows the doping profile of the photodiode in the 6N134; the same structure was used for all three Hewlett-Packard devices. Both the shallow p-region at the top surface and the substrate are connected to ground. Thus, during normal operation there are actually two depletion regions, one near the surface, and one between the n-region and the substrate, which begins approximately 9 µm below the surface. Charge from heavy ions will be collected from both regions, and charge collection from the second depletion region will extend far into the substrate.

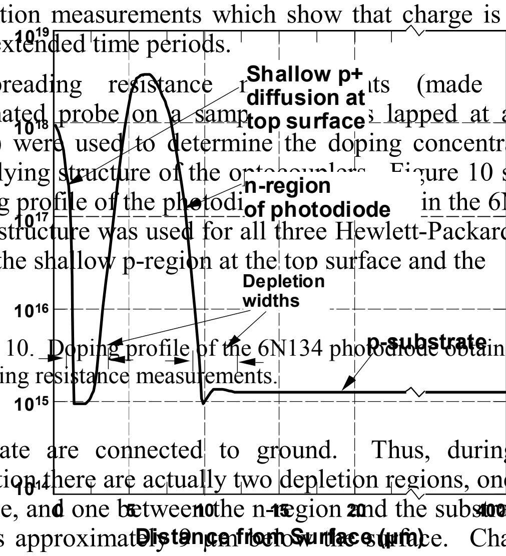


Figure 10. Doping profile of the 6N134 photodiode obtained from spreading resistance measurements.

The photodiode structure was analyzed with the PISCES device analysis program to determine how charge collection in the Hewlett-Packard devices compared with the measurements that were made on the 4N49. Those results showed that charge collection occurred far below the substrate, with essentially the same response for the two structures. Our PISCES analyses also showed that the contact to the photodiode, which occurs at the periphery in the HP devices, did not affect either the magnitude or time response of the collected charge. Simulations with different ion track lengths showed that the effective charge collection depth with long-range ions was 50 µm, very similar to the experimental results obtained for the 4N49.

IV. DISCUSSION

A. Response Mechanisms

Optocouplers are relatively simple devices. The photodiode of all three HP devices has a relatively large area (~10^{-3} cm^2), far larger than that any of the other individual components used in the integrated circuit. Near the threshold LET the response of the optocouplers is dominated by charge generated in the photodiode, which is expected because the circuit is designed to respond to small optically induced photocurrents in the photodiode. However, for LET values > 11 MeV-cm^2/mg other regions of the device, associated with the complex input amplifier, appear to make a significant contribution to the cross section. This is consistent with the complex responses observed for single-event transients in linear integrated circuits which do not contain large-area photodiodes [3-5].

The depth of the photodiode structure, the significant decrease in cross section between ions with 39 and 60 µm range (see figure 5), and direct measurements of charge from the 4N49 phototransistor with long range ions all support the conclusion that diffused charge is an important contribution to the total cross section. It is also consistent with the diffusion length of minority carriers in p-silicon with a doping level of 10^{15} cm^{-3}. Computer calculations of the time response of diode structures with similar doping levels by Dodd, et al. have shown that a significant fraction of the diffused charge is collected in time periods below 150 ns when long-range ions are used [6], consistent with our analyses of the photodiode with PISCES.

It is possible to estimate the critical charge and the effective charge collection depth from the data obtained with alpha particles and heavy ions, assuming that charge collected in the photodiode dominates the response. Assuming that all of the charge from a 3.2 MeV alpha particle (11 µm range) is collected by the photodiode, the pulse width of the 6N134 is 40 ns (see Figure 8). Thus, a charge of 0.14 pC will produce a 40 ns pulse. The same pulse width will occur for a long-range particle with LET = 0.3 MeV-cm^2/mg. Our PISCES simulations show that 95% of the charge from a long-range ion will be collected within 40 ns. Assuming that the optocoupler amplifier is charge dependent in this region (which is just above the response threshold), then the same charge will be required to produce the same pulse width from short and long range ions. The effective charge collection depth for long-range ions is then 49.1 µm. This result, which is based on experimental measurements, is also consistent with the charge collection depth obtained in PISCES simulations.

As shown by the pulse width histograms in Figure 2, the net response of devices with high-gain amplifiers depends on the response of the amplifier to charge collected at sensitive nodes within the amplifier as well as charge collected in the photodiode. The response of the amplifier begins to become important for LET values above 2 MeV-cm^2/mg. For heavy ions with LET > 11 MeV-cm^2/mg, amplifier responses will actually dominate the response and extend the pulse width to much longer values.

B. Response in Proton Environments

The present heavy ion results and charge collection evaluation can be used to interpret proton tests that were previously reported for the HCPL-5631 [1] (recall that the HCPL-5631 is identical to the 6N134 except for package type). Proton experiments with different incident angles showed that the cross section was independent of angle for incident angles below 80°. When the angle of incidence was increased further, the cross section began to increase; it was about a factor of ten larger at 90° compared to the cross section at moderate angles. This result was unexpected. An analysis of the angular dependence in the previous work was done to take direct ionization from protons into account along with the proton reaction products. They assumed a very shallow charge collection depth (2 µm) in their analysis, which resulted in a much steeper angular dependence at angles near 90° than was observed experimentally [1]. The cross section did not increase to the point that it could be entirely due to direct ionization from protons.

The present heavy-ion measurements show that the effective charge collection depth for long-range particles is about 50 µm over a time interval of 100 ns, the approximate value of transient pulsed from the optocouplers with internal amplifiers. This is consistent with charge collection simulations by Dodd, et al. [6] as well as our own work on charge collection, assuming a diffusion length of 60 µm in the p-substrate. Note that the ion range must extend well beyond the effective charge collection depth to collect charge corresponding to that value [6,12].

Although it is reasonable to assume that the 50 µm charge collection depth will apply to direct proton ionization (the protons have a very long range), it is less obvious how to deal with charge collection from the short-range recoil products. One normally assumes that recombination will reduce charge collection from short-range particles unless the charge they deposit is located very near the depletion region. Thus, the sensitive region where proton recoils can affect the optocouplers is expected to be much less than 50 µm. Note, however, that the optocoupler amplifier produces pulses between 20 and 200 ns in width, implying that it is sensitive to charge collected over a much longer time interval than for most conventional digital circuits. Extending the charge collection time interval may influence the physical region where diffused charge can affect the optocouplers, and thereby affect the analysis of the angular dependence.

A series of PISCES simulations was done to determine the magnitude and time dependence of the photodiode to short-range particles (similar to proton recoils) that traverse regions well outside the depletion region. A 3.5 µm track with a charge density of 0.1 pC/µm (LET approximately 10 MeV-cm^2/mg) was placed at four different locations outside the depletion region of an n-p diode. Figure 11 shows the location of the tracks, along with the doping levels and device geometry used in the simulation (a slightly simplified version of the photodiode of the Hewlett-Packard optocouplers).

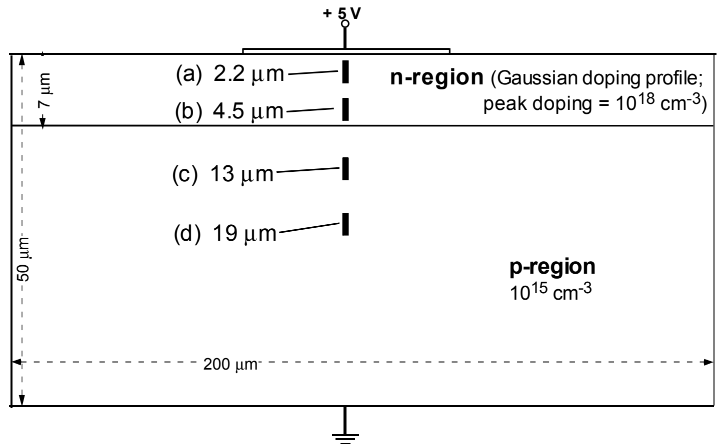


Figure 11. Geometry and track location used for PISCES simulations for tracks located beyond the depletion region.

The results of the simulation are shown in Figure 12. For short time periods -- representative of circuits that respond very quickly to SEE pulses -- very little charge is collected when the charge track occurs outside the depletion region. However, that is not the case for longer time periods where a significant amount of charge is collected by diffusion. At 20 ns nearly ½ the total charge is collected for a track centered at 19 µm, 9 µm beyond the edge of the depletion region. Extending the charge collection time to 40 ns allows nearly 70% of the charge to be collected by an ion at 19 µm.

Thus, although the charge collection depth for short-range particles is clearly less than for long range particles, the simulations show that the total charge collection depth – including the top region of the diode – is about 25 µm for circuits that integrate charge collection over time periods of 40 ns, nearly ½ the charge collection depth for long-range particles, and about 10 times thicker than the charge collection depth assumed by LaBel et al. [1]. This result is somewhat surprising, because one normally assumes that proton recoils have to be located within (or in close proximity to) the depletion region in order for their charge to be collected.

The revised charge collection depth changes the geometry of the charge that is contributed by direct ionization and reaction recoil products from protons. The charge collection

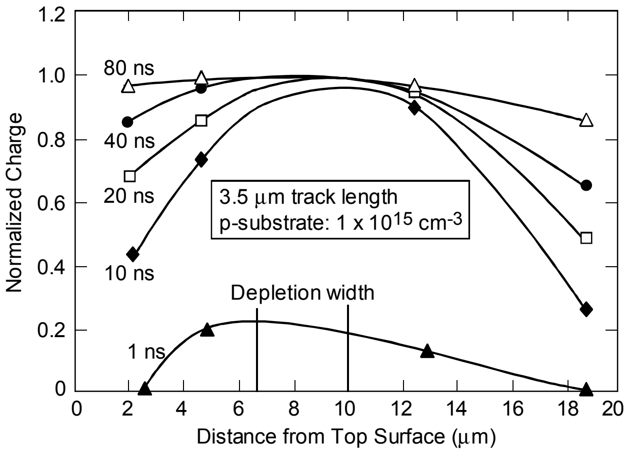


Figure 12. Fraction of charge from 3.5 µm that is collected at various time periods (from PISCES simulations)

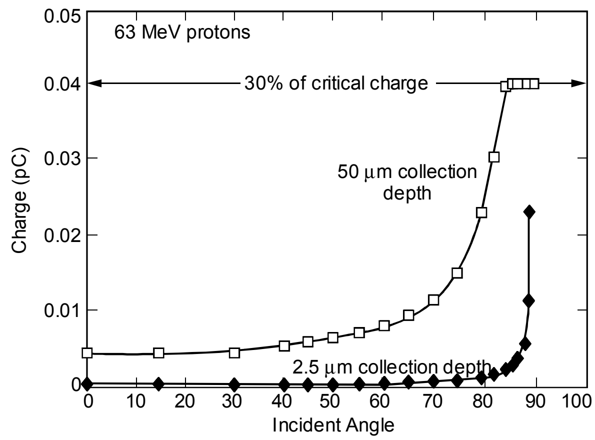


Figure 13. Calculations of the effect of incident angle on collected charge from direct ionization for protons using two different charge collection depths. The results with the longer charge collection depth show a much more gradual increase with incident angle.

depth at normal incidence for the 6N134 is almost exactly 1/10 the diameter of the photodiode. Let us assume that the increase in cross section at large angles is due to the superposition of a weaker direct ionization component (which will occur for each proton, not just those that interact with the lattice to produce recoils) with charge from the proton recoil. For 63 MeV protons, the maximum recoil energy is about 8 MeV. There will be a continuous distribution of recoil energies [8,9]. As shown by our alpha particle results, the threshold energy† for transients in the 6N134 is about 3 MeV, corresponding to a critical charge of approximately 0.14 pC. The charge collected from the direct ionization component of a normally incident 63 MeV proton is 0.004 pC, about 3% of the critical charge. At 80°, simple geometrical calculations show that the direct ionization component will increase to about 0.024 pC, approximately 20% of the critical charge; the total path length is 60% of the diameter of the photodiode in the HP optocouplers. Figure 13 shows how the charge from direct ionization is affected by incident angle for the shorter charge collection depth assumed in Reference 1 and the longer charge collection depth based on the present work. The angle dependence (ultimately limited by the diameter of the photodiode) is much more gradual for the longer charge depth, but is still less than the critical charge even at 90°.

For 63 MeV protons, charge from direct ionization alone cannot cause upsets in the optocoupler even if they pass through the maximum diameter of the photodetector. However this may be possible with protons of lower energy, which have higher LET. The effect of direct ionization is to provide an incremental increase to the total collected charge beyond the contribution from proton recoils; the magnitude of this direct ionization component depends on the incident angle of the proton. The net effect on the cross section is complex, and must consider the distribution of proton recoil energies as well as the charge collection geometry. Figure 14 shows how the fraction of recoils is affected by direct ionization (see references 8-10 for a discussion of proton recoils). A relatively small "shift" due to the incremental increase in charge from direct ionization makes it possible for recoils with significantly lower energy (and increased abundance) to cause the device to respond. This results in a much larger increase in the number of recoil atoms that can cause the device to respond than one would normally expect from such a small change in collected charge. Note however that the net effect on the cross section is somewhat lower than would be predicted from the distribution of recoils alone because the solid angle for the direct ionization component is reduced at large incident angles (see reference 10).

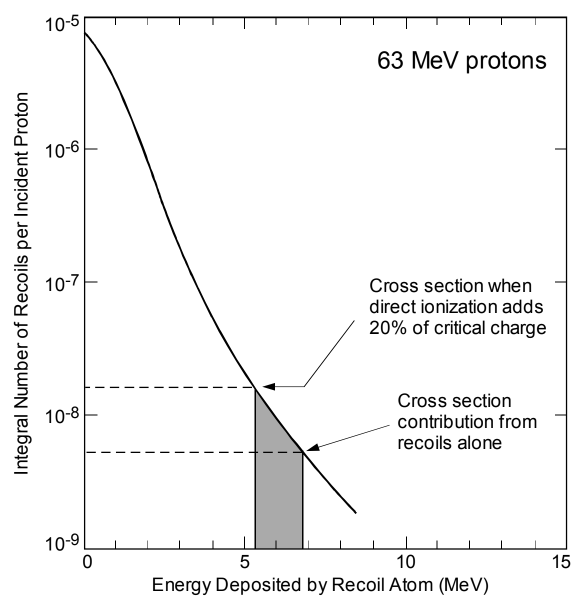


Figure 14. Effect of incremental direct ionization component on the fraction of recoils that can produce upset effects.

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†This equivalence is based on pulse width, not cross section. Pulse width near threshold is almost exactly proportional to alpha particle energy and heavy ion LET, and does not depend on the definition of threshold LET from the standpoint of the cross section (see Figure 8).

V. CONCLUSIONS

The very low threshold LET and relatively high cross section of optocouplers with complex internal amplifier stages results in error rates from GCR (solar minimum) that are about 0.25 upsets/day in a deep space or GEO environment. These upset rates are far greater than the upset rates expected for most linear integrated circuits, and are due to a combination of the large area of the photodiode and the high gain of the internal amplifier. Error rates for simpler types of optocouplers (such as the 6N140) are more than two orders of magnitude lower, primarily because there is no high-speed high-gain amplifier, and the threshold LET is thirty times higher unless they are used in very unusual circuit applications. Although optocoupler transients will not always cause operational difficulties, the pulse width of these devices when they are irradiated with heavy ions is much longer, with full (saturated) amplitude, than test results with protons. Thus, in many cases logic circuits driven by these optocouplers will respond to nearly all of the pulses produced by heavy ions if they are used in asynchronous applications. The response of optocouplers to heavy ions is a potentially severe problem that needs to be carefully considered in space applications.

Although one would normally expect that transients in these devices would be dominated by the large-area photodiode, the test results show the presence of a second component, associated with the high-gain amplifier, that can extend the pulse width to much longer time intervals for LETs above approximately 10 MeV-cm^2/mg. The ion range must be greater than 50 µm in order to correctly simulate the pulse width for transients in these devices from heavy ions in space. Particles with shorter range not only have a lower cross section, but also produce pulses with more narrow width than particles with longer range. The presence of the second component results in a complex distribution of pulse widths for these devices, much like that of transients in other linear circuits that is evident at higher values of linear energy transfer.

Although the two optocouplers with high gain amplifiers were far more sensitive than more basic optocouplers with simple transistor amplifiers, other types of optocouplers are available with considerably more optical sensitivity. Such devices will likely be even more sensitive to transients from protons and heavy ions, and this needs to be considered when selecting optocouplers and related optoelectronic devices for space applications.

APPENDIX

A. Amplifier Response Time

Response time and gain of high-speed amplifiers are interdependent. For a basic transistor amplifier, response time is ultimately limited by the base transit time [11]. By heavily overdriving a common-emitter amplifier, the response time approaches $1/(2\pi f_T)$, where f_T is the gain-bandwidth product. For npn transistors with moderate voltage ratings, f_T is typically in the range 300-600 MHz, with maximum response time of 0.27 to 0.54 ns. This does not consider the effect of the RC time constant of the collector, which reduces the maximum response times to much lower values in most circuits.

For a simple optocoupler with an open collector, the response time to short-duration pulses from heavy ions is limited by the gain of the transistor rather than the fundamental response time (speed) of the transistor because the transient current pulse is small, forcing the transistor to operate in an active or weakly saturated region (unless the collector load current is very small). Under these conditions, the rise time is exponential.

For a step function current pulse, the collector current i_c of a common emitter amplifier is

$$i_c = h_{FE}\, I_B(1 - e^{-t/\tau}) \qquad (1)$$

where h_{FE} is transistor gain, I_B is the base current, and the time constant $\tau = h_{FE}/[1/(2\pi f_T) + R_L C_L]$, with f_T = gain-bandwidth product, R_L = collector load resistance, and C_L is the capacitance at the output. This extends the response time to 150-300 ns for h_{FE} = 500 under conditions of low input drive. The response time can only be reduced by providing higher drive current. Thus, the output current drive of a simple transistor amplifier is limited by small-signal input conditions rather than the fundamental response time of the amplifier.

Incorporating high-speed circuits into optocouplers provides additional gain, allowing the circuit to respond more quickly to a small input current pulse compared to a basic transistor amplifier. Although the circuit used in the HP134/5203 is proprietary, such amplifiers are typically heavily overdriven and use multiple gain stages to increase the sensitivity and response time.

B. Circuits and Measurement Criteria

1) Optocoupler Transients

Linear transients depend much more strongly on circuit application details than SEE effects in logic circuits [3,4]. Because optocouplers provide input signals only through the input photodiode, one does not have to consider input threshold and overdrive effects, which simplifies characterization and interpretation. Output loading, however, is still an important consideration.

Manufacturer's data sheets show that output loading conditions have a relatively small effect on the optical input threshold for devices with internal amplifiers. Changing the load resistance from 1 kΩ to 4 kΩ shifts the transition point for LED input current by only about 20% for the 6N134/5203 devices with high-gain amplifiers. This implies that the threshold LET would change by the same amount for load conditions between 1.25 and 5 mA (we used a 2.4 kΩ load resistor, a 2 mA load condition, in our tests with a 5-V power supply).

Output loading has a more direct effect on devices with simple transistor amplifiers. In most cases the output RC time constant will limit the response time when a five volt logic swing is used. The response time of these devices is highly circuit dependent, and much slower than that of devices with internal amplifiers.

Transients from these devices were measured with an oscilloscope, using a triggering threshold of 20 mV. Each individual waveform was saved, which allows the effect of changing the definition of a threshold amplitude (or pulse width) criterion to be examined after the experiments are completed. This is a more flexible approach than that used in experiments which use optocouplers to drive logic gates.

Load capacitance is also important for linear transient experiments. The load capacitance was about 5 pF, which is representative of most circuit applications. The output RC time constant was 12 ns.

2) Charge Collection Measurements

A different approach was used for charge collection measurement of the 4N49. The transistor was connected as an emitter follower, driving a 100-Ω emitter load. The base was connected to a voltage divider (18 kΩ to 5 volts; 11 kΩ to ground) which was effectively a 6.8 kΩ load resistance from base to ground. This circuit provides much faster response time compared to common-emitter circuits, although the gain is much lower. The purpose of these measurements was to measure the diffused charge component and to verify that charge collection extended to relatively long time periods. Simulations with the SPICE program produced waveforms with nearly identical waveforms to those observed experimentally in Figure 9.

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