IEEE Transactions on Nuclear Science, Vol. NS-30, No. 6, December 1983

Charge Collection Measurements for Heavy Ions Incident on n- and p-Type Silicon*

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ABSTRACT

We present the results of charge collection measurements for heavy ions incident on n- and p-type silicon for a range of doping densities and bias conditions. The total collected charge agrees reasonably well for most particles with the simple model we presented last year. However, the model begins to break down for very highly ionizing particles. The experiments also indicate that the collection time increases with ionization density, so that significant recovery of the struck junction may occur during the collection process. We also found that recombination is only a small effect; and the charge collection does not seem to depend strongly on angle of incidence, at least for the cases where we performed measurements. We discuss the implications of all these findings for circuits operating in a cosmic ray environment.

INTRODUCTION

Ever since soft errors in semiconductor memories were first reported,[1] concern has been growing about the effect when integrated circuits are scaled down in size. In 1981, Hsieh, Murley, and O'Brien[2,3] reported enhanced charge collection by rapid drift currents (as opposed to slow diffusion currents), which they termed the field funnel effect. The concern has been that the funneling of charge to a circuit node would make more circuits sensitive to single event upset than originally expected. Several models[4-6] of the funnel effect have been presented, with varying degrees of complexity. In 1982, we reported a simple phenomenological model of the funnel effect based on the concept of an effective funnel length.[4] We also reported measurements of enhanced charge collection in p^+-n junctions in n-Si and in n^+-p junctions in p-Si exposed to incident alpha particles for a range of resistivities and bias conditions. Our simple funnel length model indicates that the funnel effect should be much more pronounced for high LET (linear energy transfer) particles, such as high-Z cosmic rays. Because of the interest in predicting single-event upsets in the space environment, we have performed a series of charge collection measurements for heavy ions incident on Si to test the predictions of our model. In this paper, we review the model, describe the experiments, present the results, and discuss their implications.

REVIEW OF MODEL

The simple phenomenological model of the charge funneling effect, which we used to estimate the total prompt charge collection (by drift) for alpha particles incident on Si substrates,[4] is based on the concept of an effective funnel length over which the drift fields and currents exist in an average, overall sense. The basic assumption of the model is that charge separation between the electrons and holes in the ionization wake of the incident particle occurs near the outer edge of the expanding plasma column where the carrier density is of the order of the background substrate doping density. It is assumed that the interior core of the column remains closely charge neutral, and that the outward radial expansion of the column occurs via ambipolar diffusion.

Within the framework of these approximations the prompt charge collection by drift, Q_c, was related to the effective funnel length L_c by

$$Q_c = q\,\bar{N}_o(L_c)L_c\ , \tag{1}$$

where q is the electronic charge and $\bar{N}_o(L_c)$ is the plasma line density (electron-hole pairs/cm) averaged over the funnel depth. L_c is formally related to the sum of the initial depletion depth under the junction and a drift distance over which charge carriers can be collected at the surface by the field penetration along the particle track. The longitudinal field along the track responsible for the carrier drift is approximated by V_o/L_c where V_o is the sum of the applied bias and the built-in junction potential. For the case of positive applied bias to an n^+-p junction and for L_c large compared with the initial depletion depth, the final result for the total prompt charge collection is

$$Q_c = q\bar{N}_o\left(\bar{\mu}_n V_o\right)^{1/2}\left[\frac{3N_o}{8\pi\beta N_A v_p D^{1/2}}\right]^{1/3} \tag{2}$$

and the collection time is

$$\tau_c = \left[\frac{3N_o}{8\pi\beta N_A v_p D^{1/2}}\right]^{2/3} \tag{3}$$

Here $\bar{\mu}_n$ is the average electron drift mobility toward the junction, N_A is the acceptor ion density in the p-substrate, D is the ambipolar diffusion constant, and v_p is the effective charge separation (hole escape) velocity at the outer surface of the plasma column. We note that N_o (plasma line density at the surface) is different from $\bar{N}_o$ (average line density over the funnel length).

The β-factor in the cube root term of eq. (2) is a refinement of the previous model estimate,[4] and is important for treating very high density ionization tracks, such as for Cu and O ions in the present work. It enters the derivation when the radius of the expanding plasma column is scaled to the ambipolar diffusion length, L_D, via

$$r(t) = \beta L_D(t) = 2\beta\sqrt{Dt}\ . \tag{4}$$

From the assumption that the charge separation occurs at the radius where the plasma carrier density drops to the value of the substrate doping density,[4] and assuming a cylindrical Gaussian diffusive profile for the plasma particle distribution, β is determined to be

$$\beta = \left\langle\left\{\ell n\left(N_o/4\pi N_A D_t\right)\right\}^{1/2}\right\rangle \tag{5}$$

where <...> denotes an appropriate time average over the drift collection time. Use of a time average is valid because of the very weak functional dependence of β on the argument in eq. (5). For 5 MeV alpha particles, β lies in the range from 1.2 to 1.4, and since β enters the expression for collected charge only as a cube root dependence, the inclusion of the β-factor affects the alpha-particle model results by only 6 to 12 percent. However, for Cu ions and the

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* Supported by DNA/DARPA Single Event Program

doping density range in these experiments, β is 2.0-2.7 and is therefore more significant in this case.

A major focus of our previous study[4] was on the differences of charge funneling in n- and p-type Si substrates. Note that eq. (2) pertains to positive applied bias on p-type substrate; for the opposite case, negative bias on n-type substrate, the roles of electrons and holes are simply reversed. However, the strongest dependence in eq. (2) is upon N_o, the initial plasma line density ($Q_c \propto N_o^{4/3}$). One of the goals of the present study is to examine this dependence experimentally by studying charge funneling in Si using a range of ions of varying stopping power.

EXPERIMENTAL PROCEDURE

In these experiments we used the Tandem van de Graaff Accelerator at the University of Pennsylvania as the ion source. The ions used are shown in Table I along with ^{241}Am alpha particles for comparison.[7] These ions were chosen to vary dE/dx systematically over a wide range. For 70-MeV Cu ions, the stopping power is very near the maximum value we would expect to see in the normal space environment.

TABLE I

ION BEAMS

ION	E (MeV)	dE/dx (MeV/mg/cm^2)	N_o (pairs/cm)	RANGE (µm)
He	5	0.6	$4.00 \times {}^8$	25
Be	25	1.5	8.5×10^8	55
O	16	7.0	4.5×10^9	10
Si	52	13.0	8.7×10^9	17
Cu	70	31.0	2.0×10^{10}	14

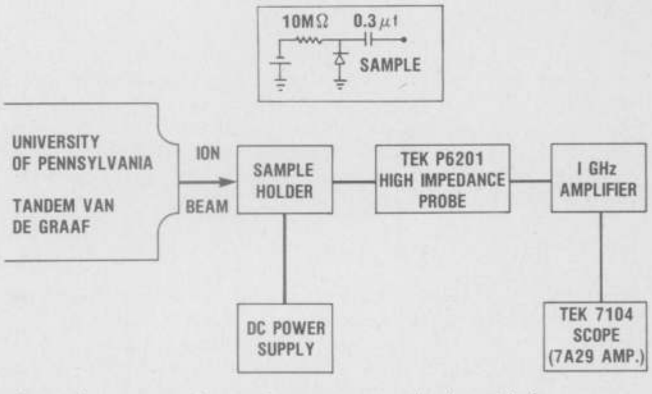

Fig. 1) Experimental apparatus (schematic).

We exposed six kinds of samples to these ion beams: three p-Si samples with N_A = 0.36, 1.8 and $5.7 \times 10^{15}/\text{cm}^3$; and three n-Si samples with N_D = 0.09, 0.47, and $2.8 \times 10^{15}/\text{cm}^3$. All but the lightly doped n-type samples were used to study the funnel effect as a function of polarity and doping density as well as ionization density. The very lightly doped n-type samples had a very thick depletion region at high biases. Most of the ions were completely stopped within the depletion layer for these samples. These lightly doped samples were used only for calibration of the apparatus to insure that we were in fact getting the right answer for the total charge. All the samples were large-area diodes (0.1 cm on a side) with a 5000-Å thick Al electrode and an 8000-Å n^+ or p^+ diffusion. The samples were made at the HDL Microelectronics Facility.

The experimental apparatus, shown schematically in Fig. 1, is similar to that described previously[4] except for the ion source. The ion beam comes into a test chamber and strikes a thin gold foil on a carbon backing. The beam scatters according to the Rutherford scattering law. The beam energy was calculated from the calibration of the analyzing magnet and the Rutherford scattering law. For all the ions except Cu, the sample was mounted at 120° relative to the incident beam. Using the backscattered beam in this manner eliminates the possibility of gold or carbon contaminating the beam. For the copper beam, we had to mount the sample at 45° and set the trigger sensitivity of the oscilloscope so that it would not trigger on C or Au contaminants which had much lower energies. The reason for mounting the samples at a forward angle is that for Cu ions scattered off gold, the nuclei are close enough in mass that the scattering is highly inelastic. The energy of the scattered Cu depends strongly on the angle, and the back-scattered beam does not have enough energy for these experiments.

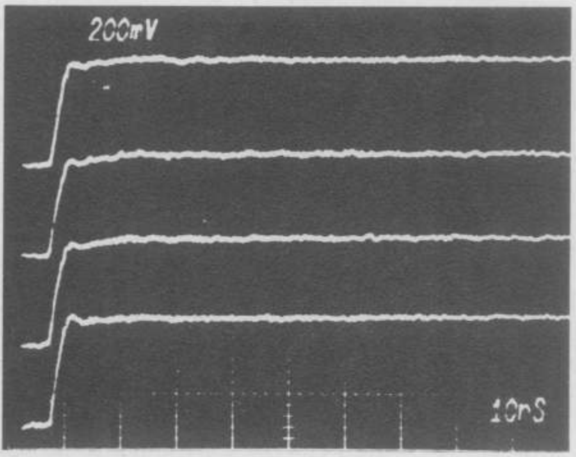

Fig. 2) Representative experimental data (Cu ions incident on p-Si ($N_A = 3.6 \times 10^{14}/\text{cm}^3$, 3 V applied).

The diodes were reverse biased (into depletion), and the signal was integrated by a wide-bandwidth (900-MHz) high impedance FET probe. Figure 2 shows representative data with the probe where the different pulses are the result of multiple exposures with the position of the trace shifted manually between pulses. The collected charge is taken to be the voltage pulse times the junction capacitance which was measured separately.

EXPERIMENTAL RESULTS

In Fig. 3, we present experimental results with the integrating probe for Cu, O, and Be ions incident on an n-type sample with $N_D = 0.9 \times 10^{14}/\text{cm}^3$ as a function of applied bias. At an applied bias of 20 V, the depletion layer for this sample is approximately 17 µm thick. Since the range of the Cu and O ions is less than the depletion width above some minimum bias, one would expect to collect the total charge generated. One can see that the measured collected charge saturates at about 3 V for Cu ions and about 10 V for O ions. Also, the measured total charge is very near the calculated total charge which is indicated by the solid horizontal lines. (In calculating the total charge, we have allowed for a 1.3-µm "dead layer" because we have 0.5-μm Al and a 0.8-μm p^+ diffusion, and we have also corrected for nuclear scattering using the LSS[8] nuclear stopping power formula.) From particle detector literature,[9,10] we would expect less than a 10 percent loss due to Auger recombination for Cu ions and a smaller loss for oxygen ions. One can see from Fig. 3 that the measured charge is less than the calculated charge by perhaps 10 percent for both ions. There is probably 10 percent experimental error in all the points, however; so we conclude that there is probably some recombination, but it is not a large effect. These results indicate that our experimental apparatus is calibrated within a few percentage points.

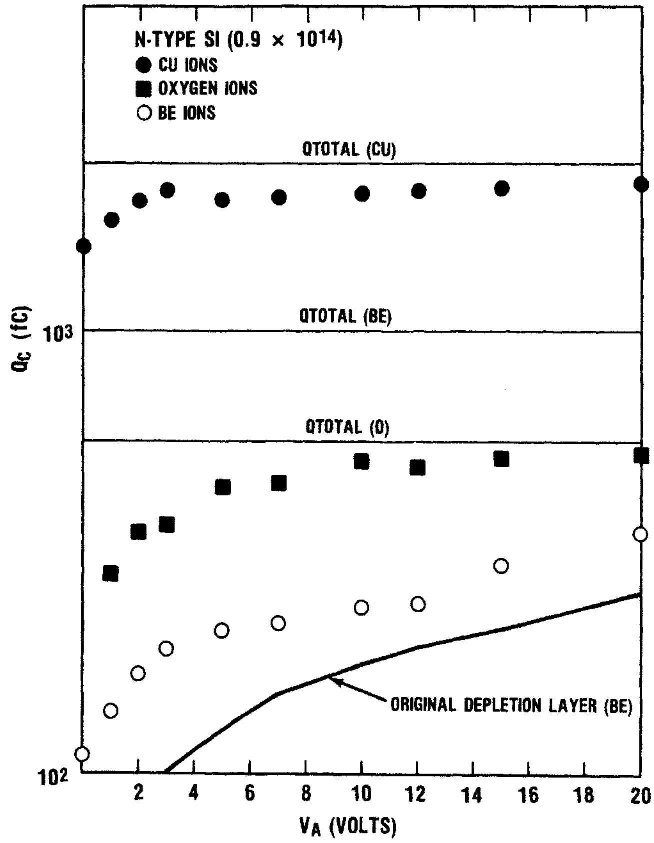

Fig. 3) Prompt collected charge for Cu, O, Be ions incident on n-Si ($N_D = 0.9 \times 10^{14}/cm^3$) as a function of applied bias.

For Be ions, the range is much greater than the depletion layer width, and the collected charge is much less than the total charge. We have shown the total charge and the measured charge for purposes of comparison. The collected charge is somewhat greater than that generated in the depletion layer, as one would expect.

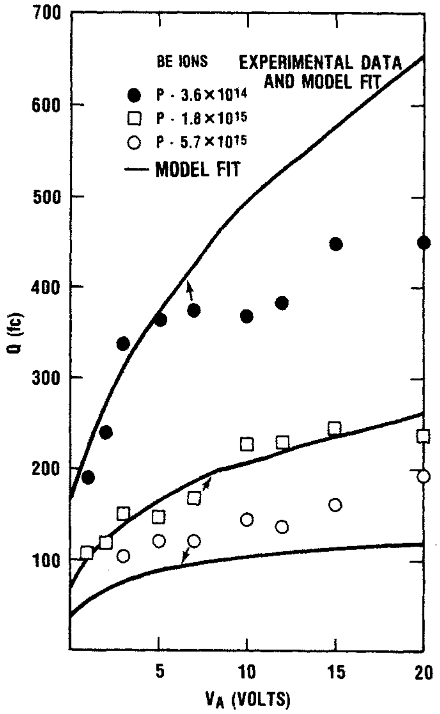

Fig. 4) Prompt charge collection measurements and model fit for p-Si exposed to Be ions as a function of applied bias.

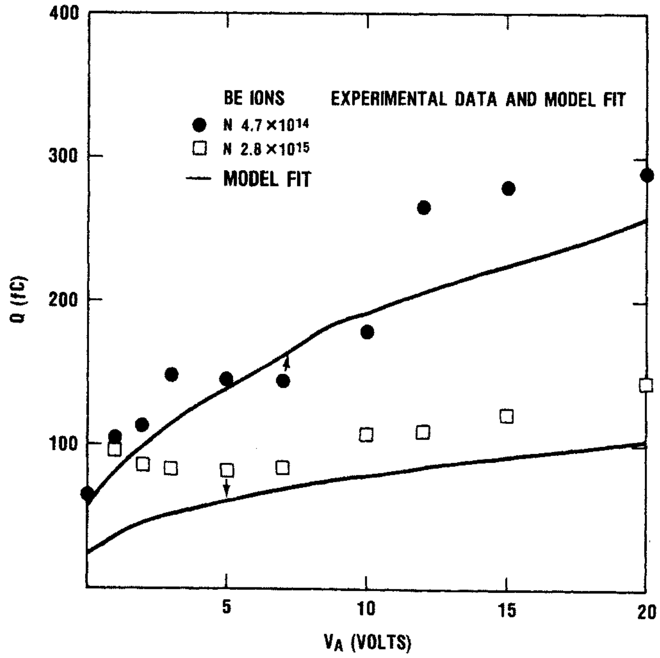

Fig. 5) Prompt charge collection measurements and model fit for n-Si exposed to Be ions as a function of applied bias.

In Fig. 4 to 6 we show results for Be ions incident on several kinds of samples. Figure 4 shows measured prompt charge collection (with the integrating probe) for three p-type samples compared to results of the model calculation. For the most lightly doped sample, the model fits the experiment and results fairly well up to about 5 V, but at higher voltages it overestimates the collected charge by an increasing margin. In the range of greatest practical interest, at 10 V and below, the worst disagreement between the model and the experiment is about 30 percent. For the most heavily doped sample the model underestimates the experiment by about 20 to 30 percent. For the middle doping density, the model predicts the results very well, within about 10 percent over the entire range of biases covered. The trend predicted by the model and observed for alpha particles, that charge collection increases with decreasing doping density, is confirmed for Be ions. Similar data are shown for n-type Si in Fig. 5. The model fits the data reasonably well over most of the applied bias range, although the model underestimates the collected charge at low biases for the more heavily doped sample. The same trend with doping density is apparent. According to the model, charge collection is less efficient in n-type material for comparable doping densities due to the lower mobility of holes (the collected carrier in this case). Some of the results in Fig. 4 and 5 are replotted in Fig. 6 to show this point more clearly. The n-type sample and the more lightly doped p-type sample have nearly the same doping density, but the p-type sample shows much greater charge collection. The other p-type sample has a doping density an order of magnitude higher but the charge collection is nearly the same as for the n-type sample. Thus, the qualitative dependences predicted by the model with respect to substrate polarity, doping density, and applied bias are all observed for Be ions. Quantitatively the model is usually within 20 percent of the experimental results. This conclusion is not really surprising since similar results were observed for alpha particles, and the ionization density is only a little more than doubled for Be ions.

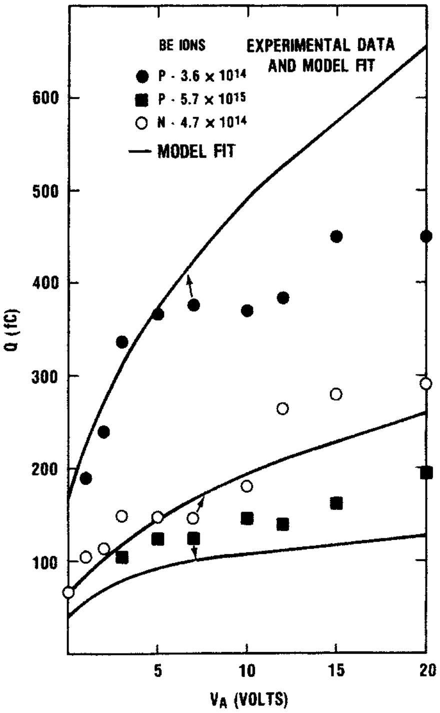

Fig. 6) Comparison prompt charge collection measurements for n- and p-Si exposed to Be ions as a function of applied bias.

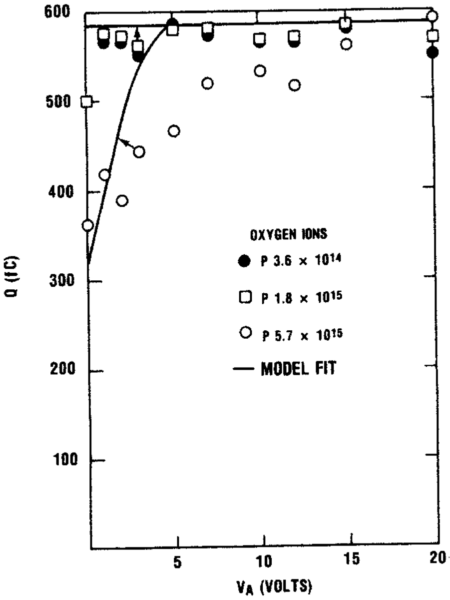

Fig. 7) Prompt charge collection measurements and model fit for p-Si exposed to O ions as a function of applied bias.

The experimental prompt charge collection results for oxygen ions are shown in Figs. 7 and 8. For p-type samples, the response of the two lightest doped materials are saturated as the model predicts (i.e., the effective funnel length is greater than the particle tracklength in these cases). For the heavily doped sample, the collected charge does not saturate as fast as the model predicts, but the agreement is within about 20 percent at the worst. For the n-type samples, the agreement is quite good for the more heavily doped material, but for the lightly doped material the model predicts saturation at lower biases, and we measure only about two-thirds of the predicted charge collection at the worst (around 2 V applied). For oxygen ions, the qualitative dependences of the model are confirmed, but the quantitative agreement with experiment is not quite as good as for alpha particles and Be ions in the worst case. (However, the model is still generally within about 20 percent of the experimental results.) For oxygen, the ionization line density is more than an order of magnitude greater than for alpha particles and about a factor of 5 greater than for Be ions.

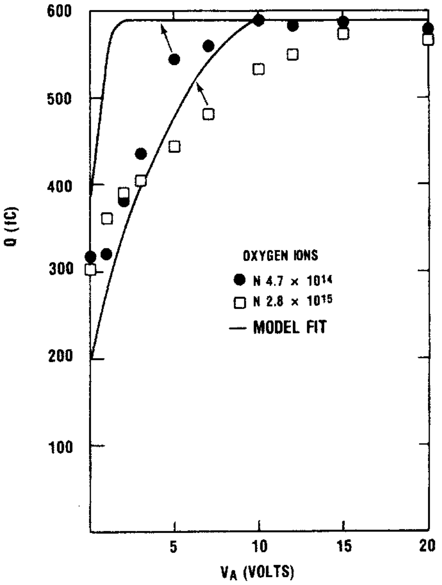

Fig. 8) Prompt charge collection measurements and model fit for n-Si exposed to O ions as a function of applied bias.

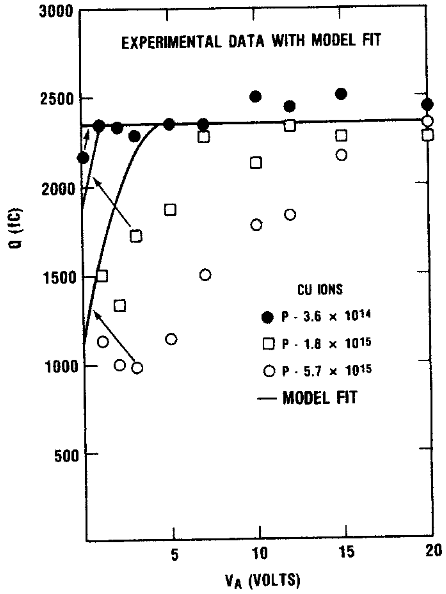

Fig. 9) Prompt charge collection measurements and model fit for p-Si exposed to Cu ions as a function of applied bias.

Prompt charge collection results for copper ions are compared with model predictions in Fig. 9 and 10. In these figures we have reduced the total charge which can be collected by 10 percent since recombination is expected to be in this range.[9,10] For all the samples, the model predicts that the charge collection will be saturated above some bias voltage and that the collection will fall off fairly rapidly at low voltages. The experimental results agree with the model reasonably well only at low biases. The measured charge collection does not saturate as rapidly as the model predicts with increasing bias voltage, although the saturation level is correct. We believe this effect may be attributed to enhanced field penetration in the neighborhood of the particle track due to strong screening effects. We discuss this point in more detail below.

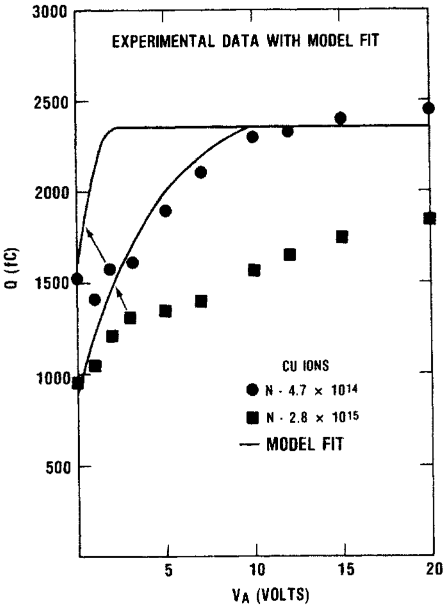

Fig. 10) Prompt charge collection measurements and model fit for n-Si exposed to Cu ions as a function of applied bias.

In Fig. 11, we show the collection times calculated from eq. 3 for two p-type samples; one lightly doped, the other heavily doped. In addition, we have plotted the exerimental collection times for Cu, O, and Be ions incident on the lightly doped samples. For Be ions at high biases and for all the ions incident on the heavily doped samples, the measurement is limited by the bandwidth of the apparatus.

In general the charge (or voltage) on the junction sensed by the measuring apparatus will be given by[11]

$$Q(t) = CV(t) = \frac{Q_o}{\tau_c} RC\ (1 - e^{-t/RC})(1 - e^{-t/\tau_R}) \quad (6)$$

for $t < \tau_c$; and

$$Q(t)=CV(t)=\frac{Q_o}{\tau_c} RC(1 - e^{-\tau_c/RC})e^{-(t-\tau_c)/RC}(1 - e^{-t/\tau_R}) \quad (7)$$

for $t > \tau_c$, where Q_o is the total charge collected, C is the junction capacitance, R is the effective resistance of the circuit (~100 k Ω of the probe in this case), τ_c is the collection time, and τ_R is the time constant of the measuring apparatus. Here we have assumed a constant current; that is, charge Q_o is collected at a uniform rate for time τ_c. There are three separate time constants in these expressions, and their interactions are not easy to unfold. In these experiments, RC is known and large enough to have little effect. In principle, τ_R can be determined also; but in this case, the system is faster than any pulse generator we were able to use for checking it. Therefore, we have not measured the system response time, but it has to be less than 1 ns. From the specifications for the probe, amplifier, and oscilloscope, one can calculate a 10- to-90 percent rise time of 0.6 ns, although it is probably slightly higher in the "real world." This value probably corresponds to an exponential time constant, τ_R, of about 0.3 ns. In principle, one could try to unfold τ_c from the response of the system at times comparable to τ_R, but this analysis is very difficult to carry out in practice for times less than a few τ_R. Therefore we have not tried to read any experimental collection times less than 1 ns, although in principle it could perhaps be done. The experimental collection times plotted as 1 ns in Fig. 11 are really 1 ns or less.

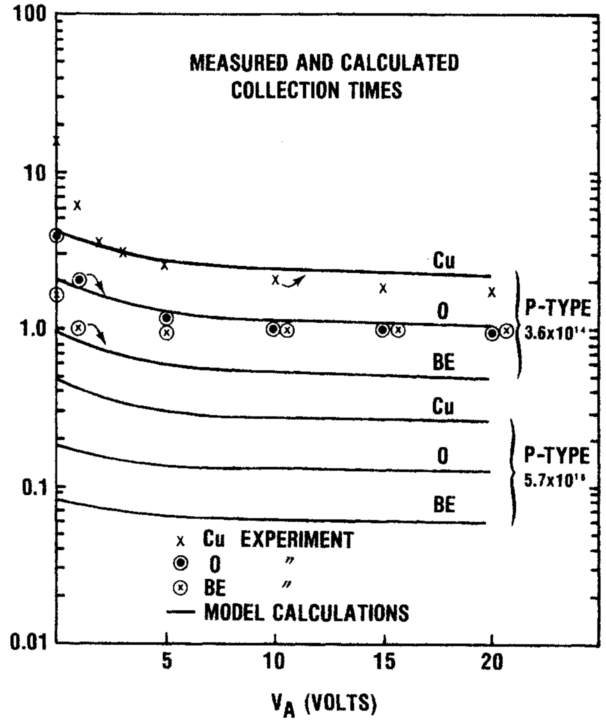

Fig. 11) Calculated collection times for two p-type samples exposed to three incident ion types. Experimental points are also given for lightly doped sample, but the apparatus was not fast enough to resolve collection times for Be at high biases or for any ions incident on heavily doped samples.

In Fig. 11, one can see that the collection times calculated for the lightly doped samples agree reasonably well with the experimental collection times down to the limit of the experimental resolution. For Cu ions, the measured collection time is slightly less than calculated at high bias. As the bias is reduced, the experimental collection increases faster than calculated, eventually crossing above the calculated curve. Over the entire range of biases, however, the experimental collection times are in reasonable qualitative agreement with the model. For O ions incident on the lightly doped sample, the experimental collection times show the same behavior as for Cu ions with changing bias; and the agreement with the model is again reasonable, although at high biases the resolution is limited. For Be ions, the collection times can be resolved only at very low biases, but the trend with bias and the comparison with the model are similar to that observed for the heavier ions.

For the heavily doped samples, one can see in Fig. 11 that the calculated collection times are roughly an order of magnitude less than for the lightly doped samples if bias and ion type are the same. We have no hope of resolving these collection times experimentally in the near future. We note that Campbell, Knudson, et al[12] have also performed charge collection measurements for these ions on a sample similar to the heavily doped sample described here. They also were unable to resolve the collection time for any of the ions. In this respect, their experimental results are similar to ours, and both can be explained by the model.

Although the experimental collection times seem to agree qualitatively with the model, we note that the agreement is far from perfect, especially at low biases. For example, τ_c is measured to be as large as 15 ns for Cu ions incident on the lightly doped sample at zero bias but the calculated τ_c is only 4.3 ns. In 15 ns, the distinction between prompt collection (by drift) and slow collection (by diffusion) is barely valid. The distance charge that will diffuse, $\sqrt{4Dt}$, for t = 15 ns is about 12μm, roughly equal to the particle track length. Indeed, for such collection times, one can almost explain the charge collection by a diffusion model, neglecting funneling. Nevertheless, the main features of the model are confirmed by the experiment, at least up to a point. That is, the collection time changes in the right direction with changes in N_o, applied bias and doping density. Furthermore, there is rough agreement between the model and experiment in all the cases that can be resolved experimentally.

Finally, we attempted to measure charge collection as a function of angle for some of the materials and ions tested. For high Z ions, the response is saturated or nearly so, even at normal incidence, because the track length is relatively short. If the particle is incident at an oblique angle, the charge will be generated nearer to the surface, but very little more can be collected. The case where an angular dependence could be important is where the track length is relatively long, and a large part of the charge is not collected at normal incidence. Of the ions we studied, only Be satisfies this description. For two p-type samples ($N_A = 3.6 \times 10^{14}$ and 1.8×10^{15}) we measured the charge collection out to 60° at 10 V applied bias and found only a 10- or 15-percent increase in the collected charge. This is comparable to our experimental error in most cases, so we conclude that the angular dependence of the funnel is slight. At larger angles, there may be more of an effect, but grazing angles are difficult to work with experimentally. For our large-area samples, even very long range particles incident at large angles would be stopped entirely in the depletion layer or even in the dead layer. One would expect total charge collection even without any funnel effect, so we did not pursue the matter in the experiments.

DISCUSSION

The model presented previously[4] predicts that the prompt charge collection will have various dependences on applied bias, substrate doping density, substrate polarity, and initial plasma line density N_o. These dependences were all confirmed last year for alpha particles, but the strongest dependence is on N_o, and we tested only one value of N_o, 4×10^8/cm, for alpha particles. In this study we have tested Be ions ($N_o = 8.5 \times 10^8$/cm), O ions ($N_o = 4.5 \times 10^9$/cm), and Cu ions ($N_o = 2 \times 10^{10}$/cm). The results of these experiments agree reasonably well for Be and O, although the O results are not quite as good as the Be results. The results agree within 20 percent in most cases, and the qualitative trends with bias and doping density are confirmed. For the highest N_o (Cu ions), the agreement is not as good; although the model and data agree in low bias limit, the model predicts a stronger dependence on applied bias than we observe experimentally. The fact that the experiment and the model agree fairly well at low biases for Cu, but not at high biases, suggests that the applied bias is not really working in this case as contained in the model. We believe this effect may be attributed at least in part to the likelihood that for some significant period of time the field may penetrate further into the substrate than assumed in the model.

One of the main assumptions that went into the present model estimate is that the field penetration down the plasma track is the same as the effective funnel length, i.e., the applied bias V_o is assumed to be entirely dropped over a distance from the junction comparable to L_c. In this way, the appropriate field-dependent value for the average mobility $\bar{\mu}$ is determined in eq. (2). This assumption appears to be valid for the lighter ions (alpha particles and Be ions). However, for the heavier ions, especially Cu ions, it may be breaking down. In particular, the screening of the initial junction field by the plasma column is so large, due to the very high electron-hole pair density (initially ~10^{20} cm^{-3}), that the field penetration into the substrate along the plasma column may be considerably greater than the effective funnel length.

In fact, for the relatively short track length of the Cu ions in Si in this study (~14 μm) only a relatively small fraction of the applied bias potential may be dropped over the track length, with the rest of the potential then appearing in the substrate beyond the plasma column. This effectively leads to a reduction in the effective voltage driving the funnel (and, consequently, a reduction in the average drift velocity of the collected carrier due to a reduction in the longitudinal field over L_c). The points of a reduction in effective drift velocity (or effective drift mobility) as well as the effect of spreading resistance due to carrier motion into the substrate at the end of the track were discussed by Messenger in his treatment of the funnel effect.[6]

Another factor which may be affecting the charge collection for the Cu ions is diffusion. As mentioned in the previous section, the model predicts charge collection times for the prompt component of 2 to 4 ns; experimental collection times in the range from 2 to 15 ns are observed. The ambipolar diffusion lengths in Si for this time regime lie between ~4 and 12 μm. Since the track length of the Cu ions is close to 12 μm into the Si, the distinction between the prompt and diffusive components of the charge collection becomes blurred; i.e., it is difficult to ascertain accurately when the prompt signal is over, leaving only diffusion current to be collected. Also, charge diffusion will tend to elongate the effective track length during the collection times, which in terms of applying the model leads to a reduction in the effective initial plasma line density. (The initial charge is spread by diffusion over a larger distance during the prompt collection time.) We conclude that the present model works reasonably well for the line density regime $N_o = 4 \times 10^8$/cm to 4×10^9/cm (alpha-particles to O ions), but begins to break down at higher values of N_o.

We should point out that this conclusion means that the model will hold for most of the particles in a space environment. We picked 70-MeV Cu ions to work with experimentally because they represent a "worst-case" cosmic ray. That is, they are as heavy as anything in the normal cosmic ray spectrum, and 70-MeV is roughly the peak in the dE/dx curve. To have a 70-MeV Cu (or Fe) nucleus strike a circuit, however, a higher energy nucleus would have to penetrate the skin of the satellite and any shielding or packaging around the electronics and then come to rest within a few micrometers of the surface of the chip. The probability of such an event must be extremely low. The high Z ions that strike the chip will probably be extremely energetic particles that pass all the way through the spacecraft. For example, a Cu ion at relativistic energies (say 1 GeV/nucleon) has a stopping power dE/dx = 1.55 MeV/mg/cm^2 or $N_o = 10^9$cm. This value is only slightly higher than that of the Be ions we have tested in these experiments, so the collected charge should also be similar to the Be results given here. Also, in calculating single event upset rates due to heavy ions, Adams[13] considers Ni ions only above energies of 160 MeV/nucleon. At this energy, Ni has dE/dx = 3.4 MeV/mg/cm^2, well below the stopping power of the oxygen ions in our experiments. We should make it clear that the ionic species does not explicitly enter into the model predictions. The ionic stopping power dE/dx is proportional to N_o, which does appear explicitly in the model. Of course, heavier ions have higher stopping powers than lighter ions at the same velocity, but the stopping power is the only thing that enters into the model calculation. Therefore, the model is sufficient for all but a few of the most heavily ionizing particles in the cosmic ray environment, where it overpredicts the prompt charge collection.

Actually we would expect a pure funnel model to break down for such ions in a circuit application even if it had accurately predicted our experimental results. As we pointed out in the discussion of Fig. 11, the collection times for very heavily ionizing particles may be several nanoseconds, and the corresponding diffusion lengths, $\sqrt{4D\tau_c}$ are several micrometers. In an integrated circuit where the devices are only a few micrometers apart, one would expect to see charge collected by diffusion on adjoining nodes during the funnel process. For the large-area diodes we have tested, this is all "prompt collected charge," but in a circuit where multiple errors are a concern, this early time diffusion would be very important. Obviously no simple empirical model such as we have proposed will account for the circuit response in such a case.

The relatively long collection times for heavier ions can have important consequences for the response of a struck junction in a circuit. According to Pickel, and Blandford[14] the recovery time of a junction in a CMOS circuit will typically be several tenths of a nanosecond. This recovery time is comparable to the collection times predicted by the model for heavily doped materials. (Real integrated circuits are typically made with relatively heavily doped materials.) For circuits exposed to alpha particles, one could reasonably use an impulse function to model the circuit response. However, the slower collection process for heavier ions will probably have to be accounted for explicitly if one wishes to model the response of a circuit accurately.

An important question is how to test circuits for single event upset. Presently a number of investigators are using Kr ions with energies around 150 MeV. Since dE/dx is greater for such ions than the Cu ions used in our experiments, and since τ_c scales with dE/dx, the collection process is presumably even slower for such Kr ions. One might even wonder if the charge collection could be slow enough that Kr or any of the heavier ions might not be a true worst case. We point out that the expression for collected charge (eq. 2) increases more strongly with increasing N_o than the collection time (eq. 3). Thus the current pulse should be larger for Kr than for lighter ions despite the longer collection time. The differences between experiment and the model for high dE/dx particles will tend to reduce the current pulse from a Kr ion relative to a lighter ion, but the data do not indicate that a lighter ion will ever actually be worse for a circuit than a Kr ion. As we indicated above, particles such as 70 MeV Cu or 150-MeV Kr are probably not penetrating enough to reach spacecraft electronics, so such ions may not really represent the worst case environment. On the other hand, circuits hardened against upset by Kr ions will have a considerable margin of safety built in -- certainly a reasonable approach.

Recently it has been proposed to test for single event upset using ^{252}Cf fission fragments.[16] Typical fission fragments are even less penetrating than 150 MeV Kr and they have higher stopping powers and plasma line densities ($N_o = 2.9 \times 10^{10}$ pairs/cm initially, although recombination will reduce this number by possibly 20 percent). The total charge generated by a fission fragment will be less than that generated by a Kr ion, however, For current sensitive circuits, fission fragments should be a more severe test for a circuit; but for charge sensitive circuits, the opposite should be true. Both Kr ions and fission fragments are much worse than most particles in the operational environment for most electronic systems.

CONCLUSIONS

We have measured the charge collection for a series of ions chosen to simulate the cosmic ray environment. The model which we developed for alpha particles (dE/dx = 0.6 MeV/mg/cm^2) holds reasonably well for particles with dE/dx = 7 MeV/mg/cm^2 or less, but it overpredicts the collected charge in most cases for higher dE/dx particles. For alpha particles, the charge collection is very fast, perhaps 100 ps, but for higher dE/dx particles, the collection times are longer. In these measurements the collection time was too short to resolve experimentally in many cases, but the model was qualitatively correct in those cases we could resolve. That is, the calculated collection times were the right order of magnitude and they varied in the right direction from one case to another, but the agreement is not precise.

The relatively long collection times are very important because significant recovery of the struck junction is likely to occur during the collection process. In some cases the collection process is slow enough that significant diffusion will also occur. This diffusion is likely to be important in integrated circuits because it can cause multiple upsets, but it has relatively little effect on our experiments with large structures.

ACKNOWLEDGEMENTS

The authors would like to thank the entire staff of the Tandem Accelerator Laboratory of the University of Pennsylvania. In particular, we wish to single out the Director, Dr. Roy Middleton, as well as Dr. D. Balamuth, Dr. L. E. Seiberling, H. White, and Dan Bybell. They all helped in important ways at different times. A special thanks goes to Mr. Bybell who spent many long hours operating the accelerator for us.

We would also like to thank James Blackburn, H. E. Boesch, and J. M. McGarrity for useful technical discussion, Raine Gilbert and Aivars Lelis for technical assistance, and B. J. Dobriansky who provided the samples.

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