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A Critical Examination of Charge Funneling and its Impact on Single–Event Upset in Si Devices†

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I. Introduction

Low–energy alpha particles emitted from packaging and high–energy heavy ions in space possess the capability of causing changes in memory state when incident on semiconductor memory cells and latch circuits [1]. This phenomenon of single–event upset (SEU) is caused by collection of charge created as the particle travels through a sensitive volume of the device. As devices are continually down–sized, the corresponding decrease in amount of charge held on storage nodes increases device susceptibility to SEU. Solutions to harden devices to SEU require an in–depth understanding of the basic mechanisms responsible for upset. Also, a detailed understanding of the charge–collection volume is critical for predicting on–orbit error rates. Previous work has revealed the formation of a field funnel in response to the particle strike [2]. Analytical models that treat the funnel in a time–averaged sense have been developed [3,4], and have been reasonably successful at predicting total collected charge for particles with low linear energy transfer (LET). Sophisticated two– and three–dimensional simulations have been used to investigate the funneling process more rigorously [5,6]; however, the interplay between the funnel and collection by drift and diffusion has remained somewhat obscure. In this paper, we present an examination of fundamental charge–collection mechanisms and the role of the funnel, using advanced three–dimensional drift–diffusion modeling. We then apply the insight gained to address radiation hardness issues in light of current technology trends.

II. Model Application: Dynamics of Charge Collection in n^+/p Si Diodes

In order to shed light on the fundamental mechanisms of charge collection, we studied the radiation response of the most basic building block of semiconductor devices, the Si n/p junction. The device we modeled consisted of a heavily–doped (5×10^{20} cm^{-3} surface concentration) n^+ diffusion in a p–type substrate whose doping was varied. We simulated two ion species in this study, a 5–MeV α–particle representing a condition of low ionization, and a 100–MeV Fe ion representing a state of high ionization in the silicon. The strike was at normal incidence and located in the center of the structure. In order to reduce computation time, we simulated only one quarter of this symmetric device.

The computed charge–collection waveform in response to a 100–MeV Fe strike (LET ≈ 28 MeV–cm^2/mg) is shown in Figure 1 for three different substrate doping densities. Of interest is the amount of charge collected in each case. The total charge generated by the ion strike is 1.09 pC (4.36 pC for the full device). The total charge collected is 1.06 pC (97.2%), 1.01 pC (92.7%), and 0.74 pC (67.9%), for the 1.5×10^{14} cm^{-3}, 1.5×10^{15} cm^{-3}, and 1.5×10^{16} cm^{-3} substrates, respectively. Of even more interest, however, is the manner in which the charge is collected in each case. While the two more lightly–doped substrates (solid and long dashed lines in Fig. 1) show only one collection regime, the 1.5×10^{16} cm^{-3} substrate (short dashed line) clearly demonstrates two collection regimes, with a breakpoint at roughly 400 ps. The reason for this behavior is readily determined from the electrostatic potential and electron concentration profiles *vs.* time, as shown in Figures 2 and 3 for the 1.5×10^{14} cm^{-3} and the 1.5×10^{16} cm^{-3} substrates. The electrostatic potential (left sides of Figs. 2 and 3) provides a snapshot of the funnel itself, while the electron concentration shows the time evolution of the plasma of charge generated by the passage of the ion. For the lightly–doped substrate, the funnel reaches a maximum depth of over 20 μm at 1 ns (left–hand side of Fig. 2a), and completely surrounds the ion–generated plasma (right–hand side of Fig. 2a). In fact, the entire plasma is located in an equipotential region corresponding to the top contact potential (red region in Fig. 2a). By contrast, the maximum funnel depth for the more heavily–doped substrate is less than 10 μm and is reached by 32 ps after the strike

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(left–hand side of Fig. 3a). Much of the generated plasma falls outside the funnel region (right–hand side of Fig. 3a). In both cases charge is collected as the funnel collapses. In the lightly–doped case, since all of the charge is confined by the funnel, there is little charge left to be collected by diffusion after the funnel collapses at 10 ns (in Fig. 2b the green region corresponds to a carrier concentration of only 10^{11} cm^{-3} following the collapse of the funnel), hence all charge collection is by funnel–assisted drift. Note that the funnel does not completely collapse until 10 ns, a much longer time period than is usually associated with drift. In the case of the $1.5x10^{16}$ cm^{-3} substrate, the funnel collapses much earlier at 400 ps, and considerable charge remains to be collected by diffusion at late times (in Fig. 3b the core of the strike region possesses carrier concentrations in excess of 10^{17} cm^{-3}). Nearly half of the total charge collected is by diffusion for this case. Note the difference in time scales between the two cases: in addition to the funnel collapse being at a much later time for the lightly–doped substrate, the funnel takes longer to reach its greater maximum depth (1 ns *vs.* 32 ps).

For incident 5–MeV α–particles, the generated carrier densities (~10^{18} cm^{-3}) are insufficient to create a deep funnel even for lightly–doped substrates, and charge collection invariably exhibits both drift and diffusion regimes. We will discuss this topic in greater detail in the full paper.

III. Model Application: Epi vs. Non–Epi Technologies

A technologically important situation to consider is that of a lightly–doped epitaxial–well structure on a heavily–doped substrate. Since the ion strike will penetrate through the well into the substrate, an obvious question is how the funneling process will be affected. In Figure 4 we show the charge–collection waveform in response to a 100–MeV Fe strike in an epi structure. The bulk response from Fig. 1 is shown for comparison. The epi structure exhibits clear drift and diffusion regimes, as well as reduced total charge collection. The reason is that the heavily–doped substrate does not support the formation of an effective funnel even for the high–density Fe strike. The epi layer is completely depleted and since no funnel forms in the heavily–doped substrate, the potential is not greatly disturbed by the Fe strike. Charge collection is therefore limited to the drift charge (*not* funnel–assisted) collected from the original depletion region, and to late–time diffusion collection.

IV. Discussion

With an understanding of the fundamental processes involved in charge collection after an ion strike, we turn to radiation hardness issues vis–a–vis technology trends. Two subjects we might reasonably explore are the implications of continued scaling, and epi *vs.* non–epi technologies. Typically, as device dimensions are reduced, the doping level is increased. One might quickly conclude that this is fortuitous, as we have just shown that higher doping levels lead to reduced collected charge. While it is true that less total charge is collected, the magnitude of the peak current increases with doping while the time to peak current decreases, as shown in Figure 5. The response of a circuit to a fast transient with a high peak will be much more severe than to the low, steady current produced by a slowly–collapsing, large funnel. In addition, the large funnel of the lightly–doped case confines the charge and may reduce multiple–bit upsets, whereas much charge is left to laterally diffuse to nearby nodes in the more highly–doped material. Since the epi technology is essentially a very heavily–doped substrate, the same arguments hold here, and this may in fact be the worst case as far as circuit response is concerned, with a very quick transient and high peak current (Fig. 5). Additionally, the lack of an effective funnel may exacerbate multiple bit errors.

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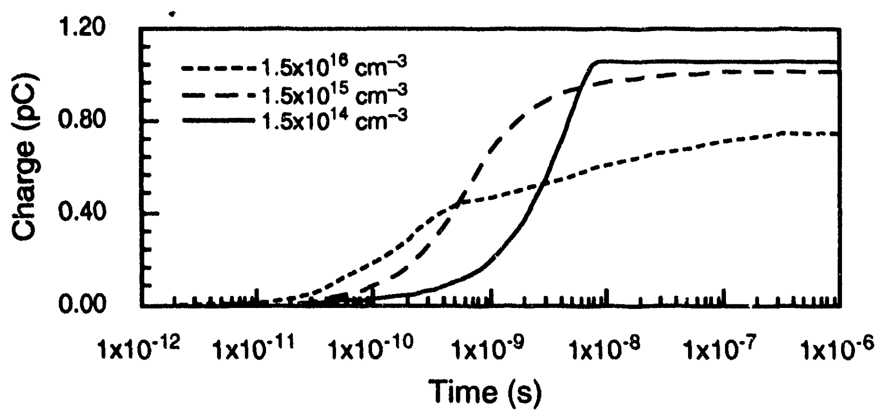

Figure 1. Charge collection in n^+/p Si diodes with substrate doping level as a parameter. The integrated charge is shown as a function of time following a heavy–ion strike.

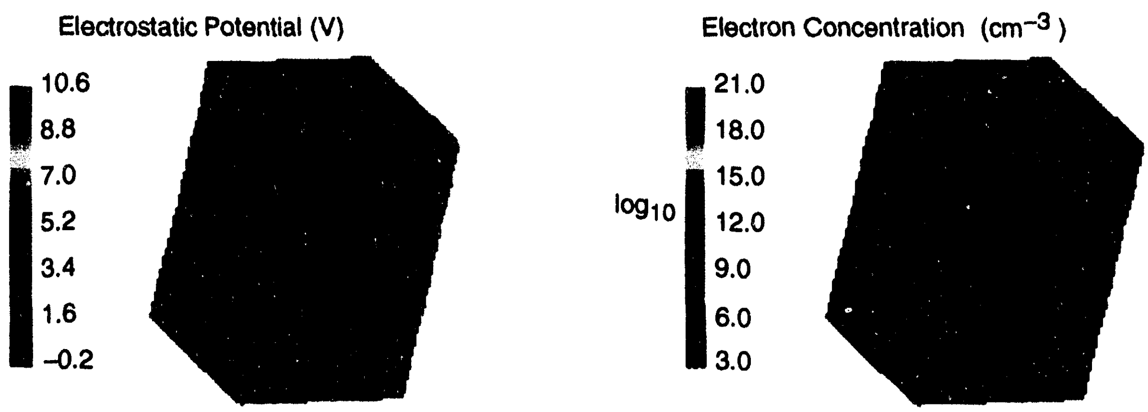

Figure 2a. Potential and electron distributions in Si diode with 1.5×10^{14} cm^{-3} doped substrate at time of maximum funnel depth, t =1 ns. Dimensions of the quarter–diode shown are 20 μm x 20 μm x 30 μm. Nominal junction size is 2.5 μm x 2.5 μm; junction depth is 0.8 μm.

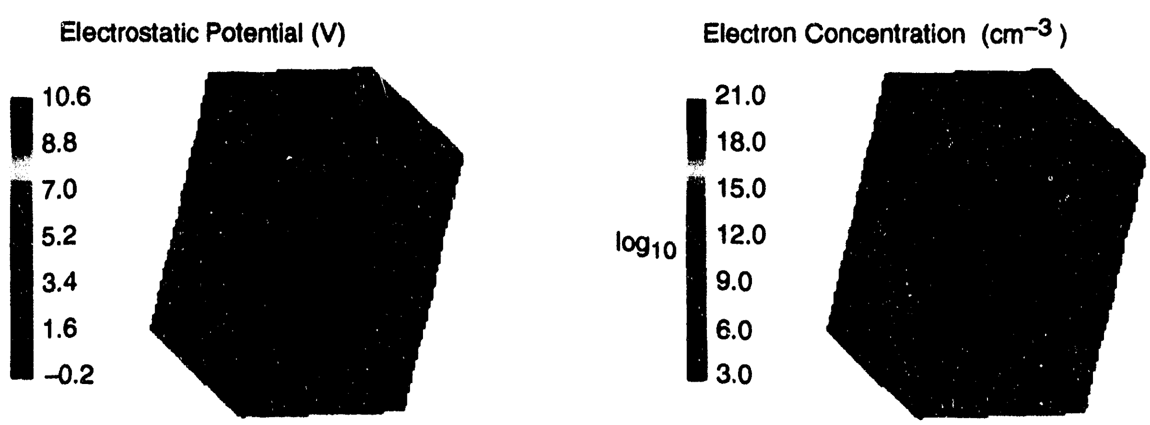

Figure 2b. Potential and electron distributions in Si diode with 1.5×10^{14} cm^{-3} doped substrate immediately after funnel collapse, t =10 ns.

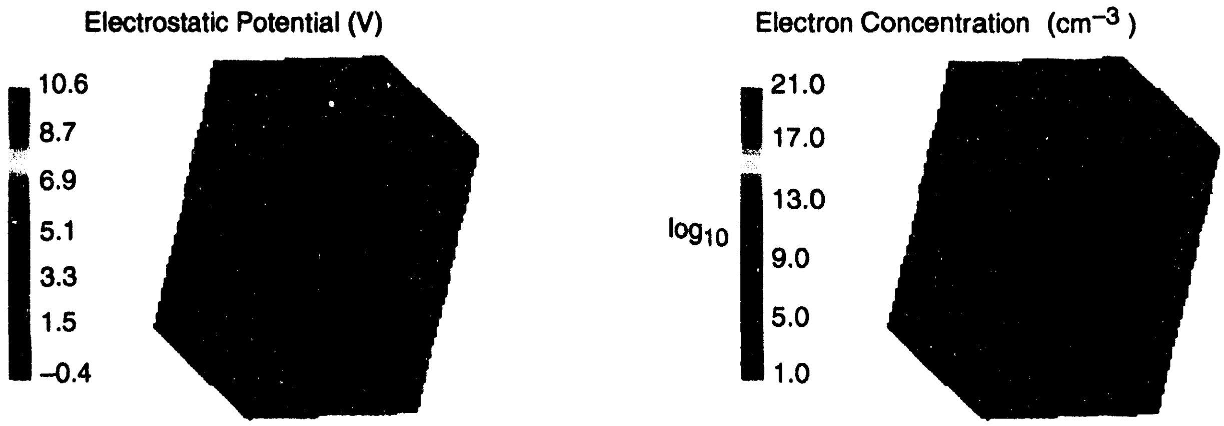

Figure 3a. Potential and electron distributions in Si diode with 1.5×10^{16} cm^{-3} doped substrate at time of maximum funnel depth, t = 32 ps.

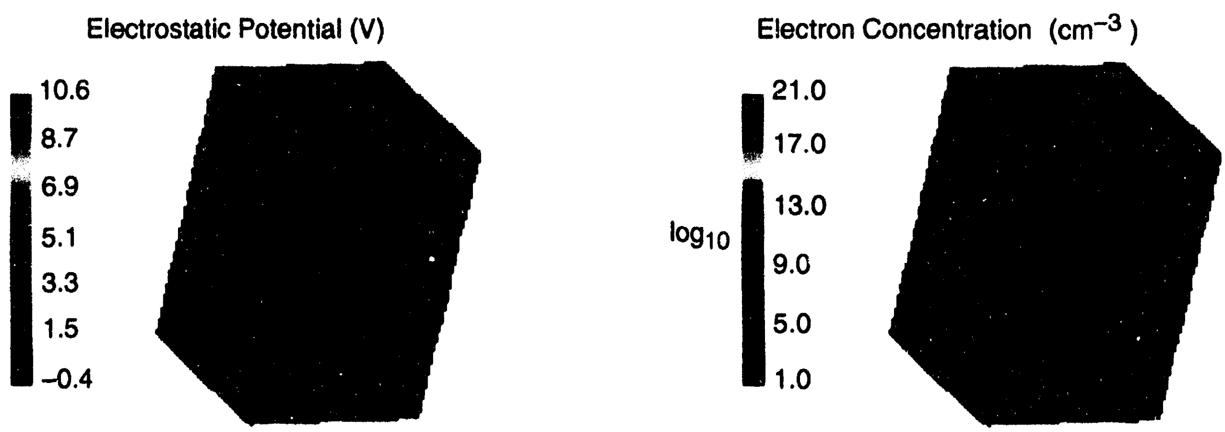

Figure 3b. Potential and electron distributions in Si diode with 1.5×10^{16} cm^{-3} doped substrate immediately after funnel collapse, t = 400 ps.

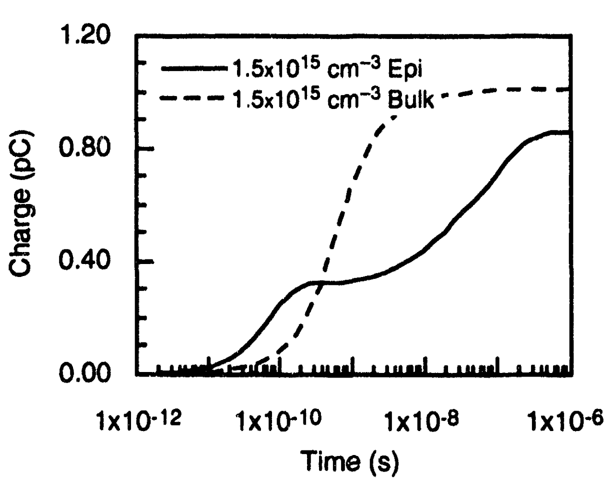

Figure 4. Integrated charge collection in epi and bulk structures. Epi structure consists of a 3 µm well doped 1.5×10^{15} cm^{-3} on a 1×10^{18} cm^{-3} substrate.

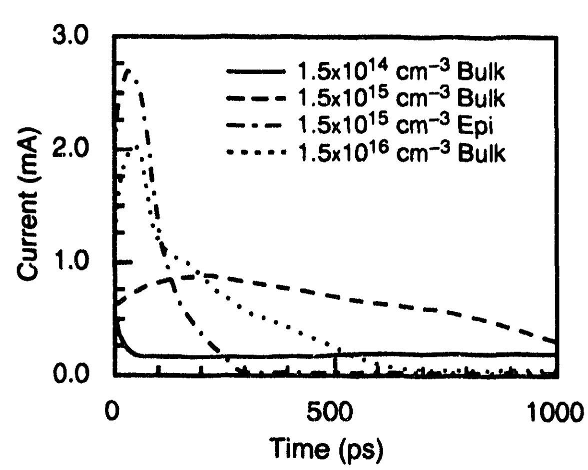

Figure 5. Current response of Si diodes to a 100-MeV Fe strike. 1.5×10^{14} cm^{-3} sample has an additional peak at ~1500 ps (off scale).

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