ABSTRACT

To design more radiation tolerant Integrated Circuits (ICs), it is essential to create and test accurate models of ionizing radiation induced charge collection dynamics within microcircuits. A new technique, Diffusion Time Resolved Ion Beam Induced Charge Collection (DTRIBICC), is proposed to measure the average arrival time of the diffused charge at the junction. Specially designed stripe-like junctions were experimentally studied using a 12 MeV carbon microbeam with a spot size of 1 μm. The relative arrival time of ion-generated charge is measured along with the charge collection using a multiple parameter data acquisition system. The results show the importance of the diffused charge collection by junctions, which is especially significant in accounting for Multiple Bit Upset (MBUs) in digital devices.
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1. INTRODUCTION

Ionizing radiation can lead to the undesirable generation and migration of charge within an IC, which can alter, for example, the memory state of a bit, and thereby produce what is called a "soft" error, or Single Event Upset (SEU). Since alpha particles, emitted by trace amounts of radioactive atoms in chip packaging materials, were found as one SEU source [1], it has been investigated by chip manufacturers. In digital devices, SEL's are the primary cause for concern, especially for SRAMs and DRAMs (Static and Dynamic Random Access Memories), and microprocessors. But the soft error rate at ground level cannot all be credited to the alpha induced SEUs. At sea level, spallation neutrons produced when cosmic rays penetrate through the atmosphere are considered the primary cause of SEL's [2]. The reason is the higher L.E.T.s (Linear Energy Transfers) for neutron-induced silicon or light ion recoils than that for alpha particles within the smaller sensitive volume.

If ions miss a junction, the induced carriers are transported via diffusion in field-free regions and may be shared and collected among charge storage cells, resulting in Multiple Bit Upsets (MBUs) [3]. MBU can pose a significant problem for SEU mitigation techniques such as Error Detection And Correction (EDAC). The response of devices to natural radiation, either alpha particles emitted by trace amounts of radioactive atoms in chip packaging materials [1] or cosmic rays generated spallation neutrons [Ziegler96], is therefore of great concern for the reliability of future devices [4]. To design more robust devices, it is necessary to create and test accurate models of induced charge collection dynamics within devices. The Ion Beam Induced Charge Collection (IBICC) technique can be utilized to simulate ion recoil effects in ICs [5,6].

In this work, Diffusion Time Resolved IBICC (DTRIBICC) is used to measure the diffusion time for the charge to be collected from the striking spot to reach the junctions using a
multiple parameter data acquisition system. With suitable start signals, the diffusion time can be easily recorded using a Time-to-Amplitude Converter (TAC). The start signals for the TAC can be triggered by secondary electrons emitted from the sample surface as a result of ions striking the sample [7]. The stop signals are the timing output from the preamplifier that is connected to the junction to measure the collected charge. Thus, the diffusion time from a specific striking spot to the junction can be recorded as a new parameter for study along with the amount of collected charge. The measured diffusion time can be regarded as the average arrival time of the diffused charge, which can be related to the first moment (or the average time) of the arrival carrier density at the junction [8]. The average arrival time can be used to window the diffusive charge collection by the junction relative to the beam striking spots.

2. EXPERIMENTAL DETAILS

Since there is no suitable trigger available at the time of the present experiments, relative arrival time rather than absolute arrival time was measured on the outer-inner diodes test structure (Fig. 1). The specially designed ICs contain various kinds of test structures. IBICC measurements from the ring-gate-inner diodes and large diode were previously reported elsewhere [9, 10]. These diodes are formed from the P and As diffusions in a p-substrate. The outer and inner diodes are separately connected through different metal pads to external package wiring. The inner diode is surrounded by the continuous 2 μm wide outer diode. The 2 μm separation between the inner and outer diodes was chosen to be the approximate node-to-node spacing of memories (Fig. 1).

A 12 MeV carbon ion microbeam (~ 1 μm diameter beam spot) produced by the accelerator at Sandia National Laboratories was chosen (because of reduced damage compared to Si) to simulate neutron-induced Si recoil effects. Other ions can also be easily substituted [6].
Three data collection channels were simultaneously used to measure the charge collection from the outer and inner diodes, and the relative diffusion time. Two separated 4 V reverse biases were applied to the outer and inner diodes through two preamplifiers (Ortec 142A). The p-substrate was grounded. The timing outputs from the two preamplifiers were fed into two Constant Fraction Discriminators (CFD, Ortec 583). The timing signals were generated in the CFD mode. The two fast timing outputs from CFDs were then fed into a TAC as the start (from outer junction) and stop (from inner junction) signals. The TAC signals were further digitized and were coincidentally recorded along with striking spot coordinates and collected charge from the two junctions. The TAC range was set at 100 ns. A 48 ns offset was inserted into the stop signal channel. Also, the time scale was calibrated with an ns delay box (Ortec DB463). The total charge collected by a pin diode was used to calibrate the charge collection electronics. The counting rate of charge collection was about $4 \times 10^2$ counts per second. The microbeam was scanned over a 60 μm x 60 μm area.

There is even an advantage of using this relative charge arrival time approach. It is assumed the charge is collected by the junction centers. Referring to Fig. 1, if the ion strikes at a distance $y_i$ from the center of the inner junction, and penetrates a distance $z$ into the sample, it is straightforward to show that this arrival time difference, $\Delta t$, is just:

$$\Delta t = \frac{(d - y_i)^2 + z^2}{D} - \frac{y_i^2 + z^2}{D} = \frac{d(d - 2y_i)}{D}$$

(1)

where $d$ is the separation between the junction centers (4 μm) and $D$ is the diffusivity of electrons in Si. It is interesting that this time difference is not a function of $z$, and therefore charge that diffuses from any point along the trajectory of the ion will diffuse to these diodes with the same $\Delta t$. 

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3. RESULTS AND DISCUSSIONS

Fig. 2 is DTRIBICC charge collection measurements on outer-inner junction test structure. In Figs. 2A and B, the images of the median filtered charge clearly reveal the inner and outer junctions, respectively. Figs. 2C and D are the cross sectional views of the slices that are defined in Figs. 2A and B, respectively. Fig. 3A plots the lateral position, Y, as a function of the relative arrival time \( \delta t \), where Y is offset by \(-25\) \( \mu m \), and \( \delta t \) is offset by the 48 ns delay. This data corresponds to positions of slice views defined in Figs. 2A and B. Eq. 1 predicts that the locus of points in Fig. 3A should be a straight line, and indeed two such lines are observed. This is because our sample geometry has two regions where the ion can strike between diodes. Fig. 3B is the histogram of the relative arrival time measurements and corresponds to the times in Fig. 3A. Figs. 2C and D are numerically coded using the measured relative arrival time measurement as shown in Fig. 3. The numerical coding 1-4 in Fig. 2C and D corresponds to the relative arrival time high counting peak at \( t=0\) ns (out of scale) and three peaks around (52-63), (44-52), (38-44) ns in the range of 38-63 ns as shown in Fig. 3B, respectively. The numerical coding also corresponds to the striking spots shown in the insert of Fig. 1.

The charge collection projections in Figs. 2C and D indicate: 1) When ions strike outside of and far away from the outer junction, the charge is collected by the outer junction through the diffusion process and no charge is collected by the inner junction. As the beam strikes closer to the outer junction, the inner junction begins to pick up some charge through diffusion. When the ion strikes outside of the outer junction, the start signals come in ahead of the stop signals. However, the charge collection by the inner junction for ions striking outside of the outer junction is not enough to trigger the CFD in the stop channel. The TAC resets itself and gives
zero output as shown in Fig. 3B (t=0 ns peak). 2) As ions strike directly or closer to the outer junction from the outside, some charge is collected by the inner diode through diffusion. Once the stop timing signals begin to be triggered, non-zero TAC signals are registered which correspond to the peak around (52-63) ns shown in Fig. 3B. 3) When the ions strike between the outer and inner junctions, the induced charge is shared between the two junctions, and the relative arrival time should follow Eq. 1. The peak around the (44-52) ns shown in Fig. 3B corresponds to ion striking between the outer and inner junctions. When ions strike in the middle of the outer and inner junctions (i.e. $y = d/2$ in Eq. 1), the TAC will record the relative arrival time as 48 ns which corresponds to $\Delta t = 0$ in Eq. 1 (Fig. 3A). If the data in Fig. 3A is fit to the straight line(s) derived in Eq. 1, the diffusivity, $D$, of electrons in Si is determined to be 18.5 cm$^2$/s.

which corresponds to an electron mobility of 714 cm$^2$/V-s. 4) The peak around (38-44) ns shown in Fig. 3B corresponds to ions that directly strike the inner junction. As ions directly strike the inner junction, the outer junction will pick up some charge through diffusion. Since there are two paths for the diffused charge reaching both sides of the outer junction, the TAC will record the relative arrival time once the diffused charge reaches the closer side of the outer junction. Considering the fact that ions scanned along AA' in Fig. 1 pass through the outer junction twice and the inner junction once, the outer junction peak around (52-63) ns has more counts than the inner junction peak around (38-44) ns. Also, the inner junction peak has a narrower half width than the outer junction peak around (52-63) ns as shown in Fig. 3B. 5) The large increases at the peaks in Figs. 2C and D indicate the transition from the outside (barrier oxide) to inside of the junctions. Also, it indicates charge collection through diffusion is not as effective a mechanism to collect charge compared with directly striking the junction, where the charge funnelling is the main charge collection mechanism. 6) Charge collection by the outer
junction in Fig. 2B revealed that there are some special features outside of the outer junction (the
gaps at y=15 \mu m and y=35 \mu m), where there is no charge collection at all by the outer junction.
Still, the charge collection beyond the gap follows the natural decay of the collected charge by
the outer junction as shown in Fig. 2D. In Fig. 2A, the gaps at y=15 \mu m and y=35 \mu m are due to
coincident measurements of the data acquisition system. Far from the gaps shown in Fig. 2A
(y<15 \mu m and y>35 \mu m), the inner junction collected zero charge (Fig. 2C).

In Fig. 4, the collected charge by the outer junction is plotted against the collected charge
by the inner junction, and the numerical labels correspond to the striking spots shown in the
insert of Fig. 1. Fig. 4 clearly reveals the charge sharing between the inner and outer junctions. 1) When ions directly strike the junctions, the struck junction will collect most of the charge, and
the other junction shares charge through diffusion. 2) When ions strike between two junctions, the charge is shared between the outer and inner junctions. This charge sharing also indicates the
ion striking spots, which is very similar to a Position Sensitive Detector. Since the distance
between the outer and inner junctions is only 2 \mu m, the position can be inferred based on the
charge sharing with potential \sim 0.1 \mu m resolution. The Y vs. \delta t data plotted in Fig. 3A also
forms the basis for a Position Sensitive Detector with similar resolution.

An off-line analysis of the collected data shows that ion induced damage did not affect
the charge collected by the junctions at the accumulated low dose rate (10 ions/\mu m^2). It is
estimated that the timing uncertainty was about 0.5 ns. Still, the timing measurement did provide
useful information to determine the charge collection dynamics.
4. CONCLUSIONS

The fundamental knowledge of charge collection dynamics in semiconductor devices due to ionizing radiation is essential for device radiation hardness assurance. The experimental results show the importance of diffused charge and charge sharing between adjacent junctions. In particular, the effect of charging sharing between adjacent memory nodes can result in MBUs. Since the MBUs are extremely difficult to diagnose and correct, the charge sharing is especially significant to account for MBUs in ICs. The order of average arrival time for diffused charge collection can be crucial to understanding and mitigating radiation induced circuit malfunctions. The investigation of this diffused charge collection using a 2D-device simulator code, MEDICI, is under way and results will be presented later.

Conclusions that can be reached based on the DTRIBICC data presented in this paper include:

1. DTRIBICC using relative arrival timing represents an important new single-ion radiation effects microscopy for studying charge sharing and measuring basic electrical properties such as diffusivity, mobility and lifetime of charge carriers in semiconductor devices or detectors.

2. DTRIBICC forms the basis for a new type of Position Sensitive Detector for MeV ions with a resolution approaching 0.1 μm. This resolution could clearly be improved by optimizing the design of the diode stripe structure.

3. The fact that very little charge was collected on the inner diode when ions struck outside the outer diodes suggests that sensitive junctions could be shielded from
distant ion strikes by using a perimeter-type diode structure. Such a perimeter shield could potentially ameliorate MBU effects.

4. The utility of diode stripes to study charge transport and sharing was clearly demonstrated in this paper. This suggests that similar structures could be used with combinatorial science approaches to quickly study and optimize the engineering of layers to reduce Single Event Effects in ICs. For example, it is easy to imagine implanting a buried charge barrier with a fluence and/or energy graded along the length of a diode stripe. A single follow-up nuclear microprobe experiment could then identify the energy-fluence required to minimize the charge that flows back to the diodes using ions that deposit charge significantly deeper than the doped barrier layer.

5. Once a suitable start trigger signal is available, the absolute average arrival time can be directly measured. Therefore, the carrier transport properties such as minority carrier mobility can be directly measured. Also, DTRIBICC could be combined with recently proposed unfocused ion beam technique, Ion Electron Emission Microscopy, to evaluate charge collection dynamics within microcircuits [7].

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REFERENCES


CAPTIONS:

Fig. 1. The outer-inner diode test structure for the DTRIBICC measurements. The inner diode consists of a 100 µm x 100 µm square region and two wings (100 µm x 2 µm) along the two edges. The inner junction is surrounded by the continuous 2 µm wide outer junction. The surface passivation oxide layer and the diffusion doping barriers are shown in the stripe-portion cross sectional view at AA'.

Fig. 2. DTRIBICC measurement on the outer-inner diode test structure. A and B are the median value images of charge collection from outer and inner junctions. C and D are the cross sectional views of the slices that are defined in A and B. Also, C and D are numerical-coded (1-4) using the measured relative diffusion time peaks at t=0, (52-63), (44-52), (35-44) shown in Fig. 3. The coding 1-4 also corresponds to the striking spots shown in the insert of Fig. 1.

Fig. 3. A is the cross sectional view of the relative arrival time measurement, which also corresponds to positions of slice views in Figs. 2A and B. The start signal was delayed by 48 ns to increase the measurement dynamic scale. B is the histogram of relative arrival time measurement on the outer-inner junctions, the peaks are shown in the range of t=0, (38-44), (41-52), (52-63). The t=0 is out of scale.

Fig. 4. Charge collection from outer junction is plotted against that from inner junction. The numerical coding is the same as Fig. 2.
Figure 1.