**Diffusion-time-resolved ion-beam-induced charge collection
from stripe-like test junctions induced by heavy-ion microbeams**

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Abstract

To design more radiation-tolerant Integrated Circuits (ICs), it is necessary to design and test accurate models of ionizing radiation induced charge collection dynamics with microcircuits. A new technique, Diffusion Time Resolved Ion Beam Induced Charge Collection (DTRIBICC), is used to measure 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. Specially designed stripe-like test junctions are experimentally studied using a 12 MeV carbon microbeam with a spot size of $\sim 1 \mu\text{m}$. The relative arrival time of ion-generated charge and the collected charge are measured using a multiple parameter data acquisition system. A 2-D device simulation code, MEDICI, is used to calculate the charge collection dynamics on the stripe-like test junctions. The simulations compare very well with experimental microbeam measurements. The results show the importance of the diffused charge collection by junctions, which is

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especially significant for Single Event Upsets (SEUs) and Multiple Event Upset (MEUs) in digital devices. The charge sharing results also indicate that stripe-like junctions may be used as position sensitive detectors with a resolution of $\sim 0.1 \mu\text{m}$.

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1. Introduction

As the charge signals defining data states are reduced by voltage and area scaling, the Integrated Circuits (ICs) have a higher susceptibility to ionizing radiation induced effects, such as soft errors (SEUs/MEUs) in memory devices [1]. The knowledge of generation and migration of charge induced by ionizing radiation within electronic devices is essential to design more radiation tolerant ICs. Studies to understand ionizing radiation induced charge collection dynamics have been widely performed, especially using ion microbeam techniques such as SEU imaging and Ion Beam Induced Charge Collection (IBICC) [2-4]. To evaluate the response of microcircuits immediately following the ion strikes, the Time Resolved IBICC (TRIBICC) has been developed to measure current transients using a high bandwidth oscilloscope and single ion striking techniques at Sandia National Laboratory [5]. In this paper, a new technique, Diffusion Time Resolved IBICC (DTRIBICC), is proposed to measure the average arrival time of charge collection and the charge collected for an ion track using a multiple parameter data acquisition system [6].

As IC design moves to a smaller scale, it is found that models based on the diffusion mechanism can interpret some experimental results better than those based on the drift and funneling assisted mechanisms [7]. The time duration of charge collection by the charge collection node can be estimated to account for the diffused charge collection [8].

Considering the induced charge at the source point x , a statistical average arrival time associated with x can provide a means to measure the speed of the charge collection process. Assume that the transient current is $I(t)$ through the node, then the total charge collection and the average arrival time, respectively, are

$$Q(\tau) = \int_0^{\tau} I(t) dt \quad \tau \rightarrow \infty \quad (1) \quad \text{and} \quad T(\tau) = \frac{1}{Q(\tau)} \int_0^{\tau} t I(t) dt \quad \tau \rightarrow \infty. \quad (2)$$

Along the ion track, a series of source nodes can be defined. Therefore, the average arrival time can also be applied to estimate the speed of charge collection for the ion track.

Model simulation results are obtained using MEDICI code (a 2-D device simulator) [9]. Based on drift-diffusion model, MEDICI can be used to study steady state or time dependent injection of electrons and holes. A localized electron-hole pair generation based on SRIM calculation along the ion track is incorporated into the codes to simulate the induced charge transportation in the device [10].

In this paper, we present experimental and model simulation results of the average arrival time on the specially designed stripe-like junction test structures. IBICC measurements from the ring-gate-inner diodes and large diode on the same specially designed ICs were previously reported elsewhere [11,12].

2. Experimental and simulation details

The Sandia microprobe, capable of multiple parameter acquisition, was utilized to produce a 12 MeV carbon beam with $\sim 1 \mu\text{m}$ beam spot size. The test structures are stripe-like junctions that are part of the outer-inner diodes. The cross section of the stripe junctions is shown in Fig. 1, and the space between inner and outer diodes are $2 \mu\text{m}$. The $2 \mu\text{m}$ separation was chosen to be the approximate node-to-node spacing of memories. The outer and inner diodes are separately connected through different metal pads to external package wiring. Phosphorus and Arsenic are used to form n^+ , and the boron doped p-substrate has a p^+ retrograde boron well. The junction doping profiles were incorporated into MEDICI simulations. The models used in simulations include carrier-carrier scattering and field dependent mobility, concentration dependent recombination, and band gap narrowing [9].

The relative arrival time was measured between the outer-inner diode test structure using the DTRIBICC technique. 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 4V 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 fast timing outputs from the 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 outer and inner 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 a nanosecond 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 4×10^2 counts per second. The microbeam was scanned over a $60 \mu\text{m}$ by $60 \mu\text{m}$ area.

There is an advantage of measuring the relative arrival time of the charge. 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, Δt , is just:

$$\Delta t = \frac{(d - |y_i|)^2 + z^2}{D} - \frac{|y_i|^2 + z^2}{D} = \frac{d(d - 2|y_i|)}{D} \quad (3)$$

where d is the separation between the junction centers ($4 \mu\text{m}$) 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 Δt .

3. Results and discussion

Figs. 2-5 are DTRIBICC charge collection measurements on the outer-inner junction test structure using a 12 MeV carbon microbeam. In Figs. 2A and B, the images of the median filtered charge clearly reveal the inner and outer junctions, respectively. Figs. 3A and B are the cross sectional views of the slices that are defined in Figs. 2A and B. Fig. 4A plots the relative arrival time projection at the same slice view position. Fig. 4B is the histogram of the relative arrival time measurements. For all data presented here, the 48 ns delay is not substrated from the experimental data. In Fig. 5, the collected charge by the outer junction is plotted against the collected charge by the inner junction. In Figs. 3-5, the numerical coding #1-4 corresponds to the position defined in Fig. 1.

In Figs. 3, and 4A, MEDICI simulation results are also plotted along with experimental results for comparisons. Based on the MEDICI simulations, the transient currents vs. time can be obtained for the outer and inner junctions, respectively. The amount of charge and the average arrival time for the outer and inner junctions can be calculated using Eqs. 1 and 2. Since simulation results show that carriers arriving later than $1\sim 2\ \mu\text{s}$ can be ignored, the values at $\tau=2\ \mu\text{s}$ are used for the charge collection and the average arrival time [6]. The simulated relative arrival time is obtained according to experimental setup, and has been adjusted with the 48 ns offset. Due to the structural symmetry along the inner junction, only half of test structure is simulated.

The projections of charge collection and relative arrival time in Figs. 3 and 4A indicate that 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. As indicated in Fig 5, the low threshold value of the CFD in the stop channel (inner junction) was about 40 fC or the minimum value of #2. If the charge collection by the inner junction is not enough to trigger the CFD, then the TAC resets itself and gives zero output as shown in Fig. 4B ($t=0$ ns peak). As ions strike directly or closer to the outer junction from the outside, more 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 at 52-63 ns shown in Fig. 4B. When the ions strike between the outer and inner junctions (peak at 44-52 ns in Fig. 4B), the induced charge is shared between the two junctions and the relative arrival time should follow Eq. 3. When ions strike in the middle of the outer and

inner junctions (i.e. $|y_i|=d/2$ in Eq. 3), the TAC will record the relative arrival time as 48 ns which corresponds to $\Delta t=0$ in Eq. 1 (Fig. 4A). If the data in Fig. 4A is fit to the straight line(s) derived in Eq. 3, the diffusivity, D , of electrons in Si is determined to be $18.5 \text{ cm}^2/\text{s}$, which corresponds to an electron mobility of $714 \text{ cm}^2/\text{V}\cdot\text{s}$. As ions directly strike the inner junction (peak at 38-44 ns in Fig. 4B), the outer junction will pick up some charge through diffusion. Since there are two paths for the diffused charge to reach 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 at 52-63 ns has more counts than the inner junction peak at 38-44 ns. Also, the inner junction peak has a narrower half width than the outer junction peak at 52-63 ns as shown in Fig. 4B. The large increases at the peaks in Figs. 3A and B 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 funneling is the main charge collection mechanism. Charge collection by the outer junction in Fig. 2B revealed that there are some special features outside of the outer junction (the gaps at $y=15 \text{ }\mu\text{m}$ and $y=35 \text{ }\mu\text{m}$), 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. 3B. In Fig. 2A, the gaps at $y=15 \text{ }\mu\text{m}$ and $y=35 \text{ }\mu\text{m}$ are due to coincident measurements of the data acquisition system. Far from the gaps shown in Fig. 2A ($y<15 \text{ }\mu\text{m}$ and $y>35 \text{ }\mu\text{m}$), the inner junction collected zero charge (Fig. 3A). Also, the irregular shape outside of the gaps in Fig. 3B is due to IC fabrication variations.

Fig. 5 clearly reveals the charge sharing between the inner and outer junctions, which also indicates the ion striking spots. Since the distance between the outer and inner junctions is only $2\text{ }\mu\text{m}$, the position can be inferred based on the charge sharing with potential $\sim 0.1\text{ }\mu\text{m}$ resolution. Therefore, DTRIBICC forms the basis for a new type of Position Sensitive Detector for MeV ions with a resolution approaching $0.1\text{ }\mu\text{m}$. This resolution could clearly be improved by optimizing the design of the diode stripe structure.

As shown in Figs. 3, and 4A, it is clear that the charge collection and the relative arrival time predicted by the MEDICI simulations are in agreement with the experimental results. We believe the difference between the experimental and simulation results are due to limitations of MEDICI code [9]. To better predict and compare with experimental results, 3D code such as DAVINCI should be utilized to simulate correct ion track and test structure [13].

Since the experimental results were recorded in list mode, 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 dose $\sim 10\text{ ions}/\mu\text{m}^2$. The relative arrival times were measured using two CFDs, the uncertainty of the CFD determined the uncertainty of the measurement. The CFDs were triggered by the rising edges of the preamplifiers. The timing uncertainty also was affected by the capacitance of the junctions. It is estimated that the uncertainty was about 0.5 ns . Still, the timing measurement would provide useful information to determine the charge collection dynamics.

4. Conclusions

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 MEUs. Since the MEUs are extremely difficult to diagnose and correct, the charge sharing is especially significant to account for MEUs in ICs. The order of average arrival time for diffused charge collection can be crucial to understanding and mitigating radiation induced circuit malfunctions.

DTRIBICC, using relative arrival timing, represents an important new single-ion radiation effects microscopy for studying charge sharing. With a suitable start trigger signal (e.g. secondary electrons from the sample surface), the absolute average arrival time can be directly measured which can also be used to calibrate TCAD tools. 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 [14].

Since very little charge was collected on the inner diode when ions struck outside the outer diodes, sensitive junctions could be shielded from distant ion strikes by using a perimeter-type diode structure. Such a perimeter shield could potentially ameliorate MEU effects. The use of diode stripes to study charge transport and sharing was clearly demonstrated in this paper. Similar structures could be used to optimize the engineering of layers to reduce SEUs in ICs. For example, a buried charge barrier with a fluence and/or energy graded along the length of a diode stripe could be implanted in an IC. 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.

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Captions

Figure 1. Cross sectional view of stripe-like junctions for the DTRIBICC measurements. The junctions are a part of outer-inner diode test structure, and the 2 μm wide stripes are separated by 2 μm wide oxide barriers.

Figure 2. Median value images of charge collection by inner (A) and outer (B) junctions.

Figure 3. Expanded cross sectional view of charge collection by inner (A) and outer (B) junctions as defined in Fig. 2. MEDICI simulation results are also plotted for comparisons. The numerical coding #1-4 corresponds to the positions shown in Fig. 1.

Figure 4. DTRIBICC relative arrival time measurements on the outer-inner diodes. A is the expanded cross sectional view of the relative arrival time (MEDICI simulation included), which also corresponds to positions of slice views in Fig. 3. B is histogram of the relative arrival time measurements. The TAC start and stop signals were triggered by the timing outputs of two preamplifier which were connected to the outer and inner junctions, respectively. The start signals were delayed by 48 ns to increase the measurement dynamics scale. The four peaks $t=0$, 52-63, 44-52, 35-44 ns are linked to the striking positions (#1-4) shown in Fig. 1. The $t=0$ peak is out of scale.

Figure 5. Charge collection from the outer junction is plotted against that from the inner junction. The numerical coding corresponds to positions defined in Fig. 1.

Figure 1

Figure 2A

Figure 2B

Figure 3A

Figure 3B

Figure 4A

Figure 4B

Figure 5