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Time-Resolved Ion Beam Induced Charge Collection (TRIBICC) in Micro-Electronics[1]

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Abstract

The entire current transient induced by single 12 MeV Carbon ions was measured at a 5GHz analog bandwidth. A focused ion micro-beam was used to acquire multiple single ion transients at multiple locations of a single CMOS transistor. The current transients reveal clear and discernible contributions of drift and diffusive charge collection. Transients measured for drain and off-drain ion strikes compare well to 3D DAVINCI calculations. Estimates are presented for the drift assisted funneling charge collection depth.

I. INTRODUCTION

Microelectronics placed into a radiation environment will be susceptible to performance degradation due to an accumulated total dose and to spurious malfunctions (SEU) induced by single ion strikes. The mechanisms for total dose effects are well understood and documented. Similarly, extensive work has been done to model and experimentally verify the mechanisms responsible for SEU. However, discrepancies between experimental results and charge collection simulations persist. As an example, the measured total charge collected after a single ion strike of a isolated FET test structure does not compare well for particular bias states with 3D charge transport device simulations[1].

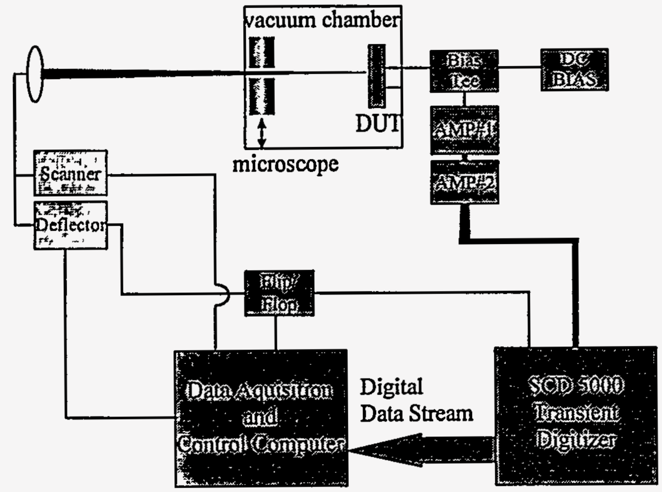

Figure 1: Schematic of experimental setup. Beam focus ~0.5µm, DUT: single n-channel 0.5 µm CMOS6 (SNL) FET, Bias Tee: Picosecond Lab (BW: 44GHz), AMP#1 & AMP#2: amplifiers (BW: 400KHz-21GHz @18 and 21 dB Small Signal Gain, respectively), Scanner: DC-to-DC HV power supplies, Deflector: 100ns 0-3KV rise time DC-to-DC power supply.

Detailed spatially and temporally dependent charge collection measurements are needed to experimentally verify transport simulations. Efforts to measure the true shape of charge transients[2,3] do not reproduce model calculations. The sampling scopes used in these experiments require 512 consecutive ion hits at one device position to acquire an entire wave form. The damage induced by repeated ion strikes[4] will affect the charge collection and can not serve as a definitive standard to which 3D model calculation should be compared to.

We have succeeded in measuring the spatially dependent current transient after an 12 MeV Carbon ion strike on a single 0.5 µm n-channel CMOS6 transistor manufactured at Sandia National Labs at an analog bandwidth of 5GHz. The measured two dimensional maps of current transients (2D-Q(t)) exhibit events with bandwidth limited 70 ps rise time events at the center of a drain and slowly rising signals (~0.75 ns) at the edge of a drain. Two-dimensional scans resulted in up to 1024 spatial charge distribution maps 2D-Q(t), each representing a time slice as short as 5 ps of the charge collected. This single-ion transient measurement as well as the spatial mapping of fast transients have never before been achieved.

Charge collection depth, a key factor in estimating error rates, can also be determined from the combination of critical charge and upset threshold. Based on the spatial information obtained with these techniques, the ability to predict upset cross sections directly from simulations will be developed. This will enable the development of SEU-hardened circuits through predictive simulations. This contrasts with the current practice of expensive and time-consuming design and fabrication variations followed by empirical tests to characterize the performance-hardness trade space.

II. EXPERIMENTAL SETUP

Great care was taken to capture the charge transient for each ion strike and to ensure a maximum analog bandwidth of at least 20 GHz for the entire signal path up to the signal digi-

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tizer. Figure 1 shows a block diagram of the experimental setup. The device under test (DUT) was mounted on a copper carrier with gate, source and silicon substrate grounded to the carrier. Signals were collected from the drain and routed to the external RF amplifiers via a 50 Ω waveguide launcher.

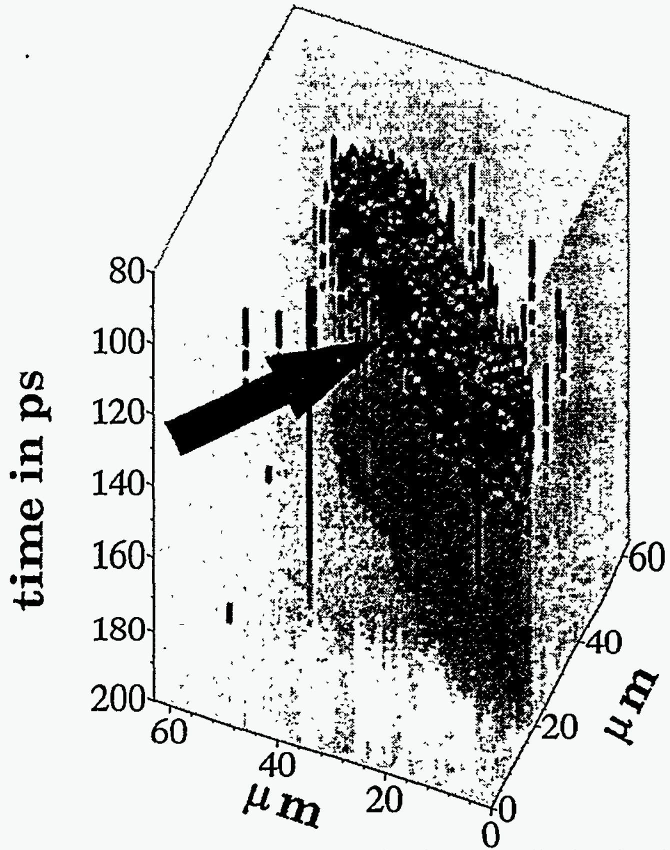

Figure 2. A representation of 4 dimensional charge collection data (2 spatial and one dimension each for time and charge). The vertical time axis represents a 120 ps time slice from the 5ns acquisition window.

The ion micro beam is focused to about 0.5 µm with a beam current of not more than 200 ions/s. A control computer manages and synchronizes the beam exposure to the target and the signal acquisition. After the 5 GHz transient wave digitizer (Tektronix SCD5000) is initialized and ready to accept a signal, the beam is redirected to the DUT by turning off the high speed (~100ns) beam deflector. The current signal is collected at the drain following an ion strike and amplified (small signal gain of 220) with a -3dB bandwidth of 20 GHz and digitized by the transient digitizer.

Because the digitization and initialization cycle of the SCD5000 after an ion strike can take up to 2 seconds, the beam has to be deflected with a minimal delay to prevent further ion strikes and therefore radiation damage of the DUT. A logic TTL is generated by the internal front edge trigger of the SCD5000 300ns after the ions strike and will set a flip/flop to high which in turn will trigger the high speed deflector and steer ion beam off the device. The probability for an additional ion strike after the first registered ion strike is $8x10^{-5}$ for a ion count rate of 200/s. While the beam remains off the target, the transient is digitized, transferred to the control computer and a new x,y target position is set before the beam is repositioned on the target.

This technique ensures that exactly only one ion strikes the device for each beam position for the composite 64 by 64 position map.

III. DISCUSSION

The irradiated n-channel device features a 0.5 µm long channel, with ~3x20µm sized and 0.25 µm deep drain and source regions. The entire structure is grown on p-type 2.7 µm thick epitaxial layer, doped at $2x10^{16}/cm^3$. The substrate is highly doped at $10^{18}/cm^3$. In addition, a p-type halo was implanted with a peak concentration of $2x10^{17}/cm^3$ at 0.38 µm. The depletion thickness at the drain-well pn-junction is ~0.15µm. The devices are capped with standard 2.0 µm thick p-glass. 12 MeV ions penetrate the entire vertical structure with little lateral spread and will range out at about 10.5 µm.

A. Data Reduction

The raw data were recorded and stored in list mode for later analysis. The maximum signal from a single carbon ion was found to drive the RF-amplifier chain beyond the -1db depression point. Hence, the amplifier gain was calibrated for the entire signal range. All subsequent data shown, have been adjusted using the amplifier gain calibration and represent the true current signal strength at the FET drain.

B. Experimental Results

Figure 2 shows a full set of 4 dimensional data taken during a 30 by 30 µm spatial scan over a single n-channel CMOS FET drain. The vertical axis represent a 120 ps time slice out of the 5ns acquisition time. One can clearly see the narrow, elongated structure of the drain represented by the dark colored area starting at the 80 ps time slice and continuing to longer times. The amount of current collected at a given point in space and time is represented through the gray scale code. The largest current is collected within the ~3x20µm drain region, while the lower charge is collected from as far as 2 µm from the edge of the drain. These features are consistent with the understanding of near-miss heavy-ion strikes.

Figure 3 shows an enlarged view of a 2D scan over the same MOSFET. The left hand side of Figure 3 represents the total charge collected at the drain after a single ion strike. This data map reveals three areas of interest. The dark area in the center of the Figure, and two lighter shaded areas to the left and right. These areas have been optically identified as the drain area in the center, the gate area to the right and the 1-2 µm area directly adjacent to the drain. The most amount of charge (on average 350 fC) is collected in the center of the drain. Ions striking within 1 to 2 µm of the drain diffusion area or close to the gate produce charge transients with an average charge of 260 fC. Note, that the total charge for direct drain hits is only 10-20% higher than "near" drain hits.

The total charge alone is not a definitive measure for the SEU cross section. Instead, the peak current collected at a node can determine if, for example, a radiation hardened static RAM cell will change its logic state. The subsequent total charge collected, albeit slow, will then determine if the device will remain in the new logic state. The right hand side of Figure 3 depicts the peak current transients measured. As before, three distinct areas of interest are discernible. The dark central area coincides with the extend of the drain. The lighter shaded areas to the left and right of the drain correspond to the 1-2 µm near drain area and the gate area, respectively.

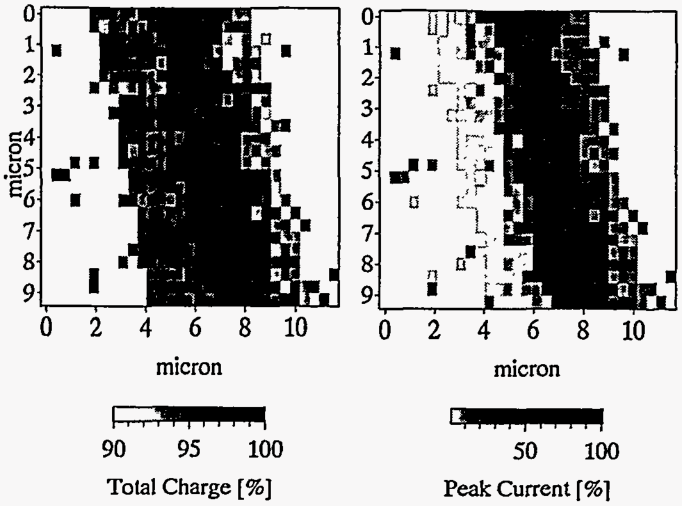

Figure 3. 2D scan over part of MOSFET. Left hand part of Figure depicts total charge collected at drain and right hand part of Figure shows peak current collected at drain.

The area to the left of the drain shows peak currents of only 5 to 10% of the maximum center drain currents. It is quite clear, that this area is unlikely to produce any upsets, although the total collected charge is only slightly less than in the drain. Ions striking the near gate areas show peak currents as high as 30% of the center drain strikes.

This map does not reveal very well the temporal evolution of the collected charge, however. Instead, a linear horizontal cut perpendicular to the extend of the drain, indicated by the bold arrow, is shown in Figure 2. This cut clearly shows the differences in the current transients between edge versus center drain hits. Ion hits, that did not produce a measurable transient were omitted. The time axis represents a 3.5 ns time slice. A rudimentary cross sectional view of the DUT and scan direction of the ion beam is inserted into the lower right hand corner of Figure 4. In Figure 4, three distinctly different groups of traces are recognizable.

The group of five traces labeled "drain edge" originate from ion strikes hitting 1 to 2 µm from the edge of the drain. This group of current transients has a rise time of ~0.75ns and a decay time of about 10ns. On average, 270 fC are collected at the drain. The pulse shape of these traces is consistent with a purely diffusion dominated charge collection. While the pulse shape does not vary significantly with strike position the amount of total charge collection is reduced as the ion strike farther from the drain edge.

Ions traversing the drain region, however, induce large, about -275 µA signals. This group of 8 traces is labeled "drain" in Figure 4 and exhibit a bandwidth limited 70-75 ps rise time and 100ps wide peak with a tail of about 10ns decay time. The rise time of the fast drain center signals are only limited by the experimental bandwidth, indicating that the drift/funnel signal is appreciably faster than the experimental resolution.

The total measured charge collected in the center of the drain is on average 350 fC of which less than 80 fC are collected during the prompt drift/funnel charge collection phase. Approximately 270 fC of this drain signal is due to diffusive charge collection. This signal group represents ion strikes in the drain region, where the fast peak is evidence of drift charge collection within the depleted pn-region formed by the drain to substrate region. Also, we expect the formation of a funnel into the epitaxial layer that will contribute to the fast charge collection. The slowly decaying component is consistent with diffusive charge collection from below the drains n^+-region. The apparent ringing has a delay time of ~350 ps and is believed to originate from the gate, source and bulk connections to ground. Changes to these ground connections are currently being implemented and data available for the final paper are expected to have a greatly reduced amount of ringing.

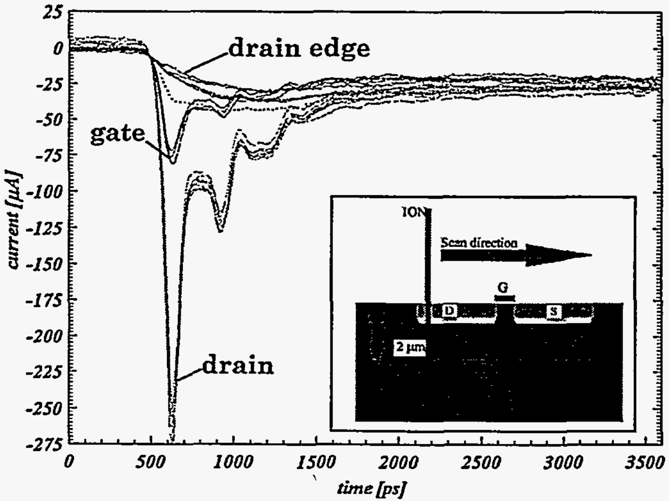

Figure 4. Current traces induced by ions striking near the drain edge, within the drain region and within the drain but close to the gate.

The last group of 3 traces, labeled "gate", arises from ion strikes traversing very close or in fact through the gate region. These transients show the same but smaller drift assisted charge collection peak with a diffusion component that is about 10% smaller than the diffusion components from drain or near drain ion strikes. The entire charge collected for these strike locations is on average 270 fC. The proximity of the grounded source may inhibit or reduce the formation of a funnel like field extension into the epitaxial layer and therefore reduces the fast drift assisted charge collection. The same argument may hold for the reduced diffusive charge collection component of these traces.

C. DAVINCI Simulations

This series of experiments presented is geared not only to further the understanding of the charge collection process, but also to validate numerical simulations of the charge collection process. The 12 MeV carbon ion hits were simulated with the three-dimensional DAVINCI code using the SNL CMOS6 FET process information as input.

The current transient results of the DAVINCI calculations implicitly assume an infinite analog bandwidth from the device drain to the current measuring point. The measurement setup used in this experiment, however, has an -3db analog bandwidth of 5 GHz. Consequently, any current transient from the device with a bandwidth higher than the experimental resolution will be broadened. It has to be pointed out, that the total charge collected will not change, but the current transient will have a different temporal evolution.

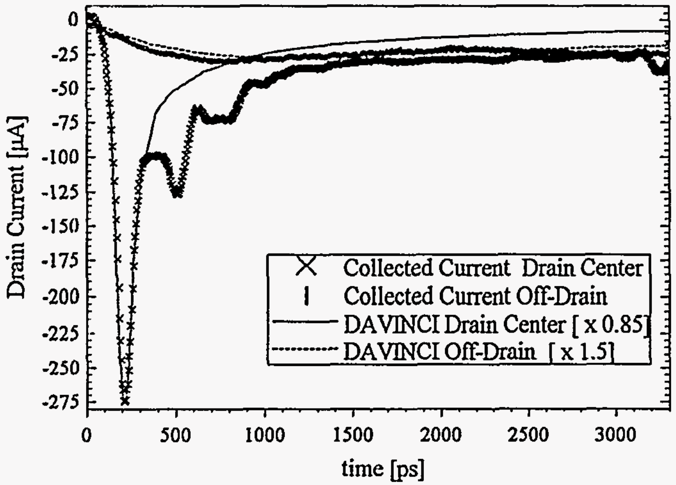

Figure 5. Measured current transient for a single 12 MeV Carbon ion striking the drain center and 1-2 μm off-drain, respectively. DAVINCI calculations are scaled to permit easy comparison to the data.

To achieve a meaningful comparison between the calculation and experiment, the calculated current transients were folded with the experimental bandwidth as follows:

$$f(t)=\int_{-\mathrm{inf}}^{+\mathrm{inf}} f(t)\times g(t)dt \qquad (1)$$

were $f(t)$ is the calculated current transient and $g(t)$ is a Gaussian distribution:

$$g(t)=\frac{1}{\sigma\sqrt{2\pi}}\times e^{\frac{-1/2\times(t-t_o)^2}{\sigma^2}} \qquad (2)$$

σ is the inflection point of the Gaussian distribution. A value of $\sigma=4\times10^{-11}$ was chosen, to result in a risetime of 70 ps for the transformed current transient.

Figure 5 depicts the experimental curves of a direct drain strike, an off-drain ion strike and the corresponding DAVINCI calculations. The calculation results have been scaled to the measurement for easier comparison. The calculations reproduce the experimental data well. In particular, the distinct rise-time and peak height differences between drift vs. diffusion are well reproduced.

The ratio of diffusion to drift charge collection, however, is not accurately reproduced in the DAVINCI simulations. For off-drain ion strikes, the diffusive charge collection is underestimated by about 50%. This difference can arise in part through an incorrect estimate of the diffusion length and life time of injected minority carriers. Furthermore, small variations in the ion strike distance to the drain area will result significant changes in the amount of diffusive charge collection. Hence, the experimental uncertainty of the ion strike location of about 0.5μm may significantly contribute to the observed discrepancy.

For ions striking the drain center we observe that the calculated drift charge collection is overestimated by less than 15%. Yet, the magnitude of diffusion is underestimated by a factor of 2-3. This difference can not be accounted for through the uncertainty in strike location nor through inaccurate minority carrier lifetime estimates. Instead, the charge collection mechanism under the drain region appears to be misrepresented.

DAVINCI does not reproduce current transients that resemble the group of transients labeled as "gate" in Figure 4. The calculated magnitude of drift assisted charge collection is similar to the center drain strike.

The experiment permits the first reliable estimate of the funneling depth. We have calculated an average energy deposition for 12 MeV carbon ions in the epitaxial layer of 120eV/Å. By subtracting from the measured center drain hit current the diffusive charge collection component and the charge collected in the 0.15μm thick depletion region under the drain one can get a funneling depth of ~1.5μm.

IV. CONCLUSIONS

The total charge deposited by a single 12 MeV Carbon ion within the 2.7 μm thick epitaxial layer, calculated using TRIM, is ~140 fC. The charge deposited in the bulk material below the epi layer during the remaining ion path of 5.6μm is ~270 fC. One has to conclude from the experimental results that during drift, funneling and diffusion charge is collected from well below the epitaxial layer in order to collected the measured charge. The peak height of the prompt (~100ps) charge collection seen in the drain region is a clear indication that funneling occurs and serves as an experimental verification of the actual funnel depth.

Because only one ion is required for each current transient, oxide charging and nuclear displacement damage to the FET is not an issue and can not influence the resulting transient measurement. The influence of the FET bias is expected to increase both, the drift/funneling as well as the diffusive charge collection.

In general, the 3D DAVINCI calculations reproduced the measured transient very well. However, the diffusive charge collection in particular for center drain strike are underestimated and may point to a deficiency in the model. Future work is planned to expand the experimental efforts to include other ions species, different FET bias states and to achieve a higher charge collection bandwidth of 15 GHz. In particular, the higher bandwidth capabilities will result in a more rigorous comparison to model calculations.

Although only ~20% less charge was collected from ion strikes at the edge of the drain, both, the amount and rate of charge collected will determine if a circuit will upset when struck by a charged particle. Clearly, the fast transient from the drain center will be more effective in upsetting a circuit than the slow transient measured at the drain edge.

The intent of this technique is to develop a new methodology for designing SEU-hardened ICs for reliable systems. The information will yield experimental verification of computer models currently in development and will provide a basis for a predictive simulation capability. Model-based design trade-off studies between SEU sensitivity, performance, and process complexity will be vastly cheaper, with significantly shorter development times, than the current process of determining SEU hardness *a posteriori*. Empirical measurements alone add little basic physical insight which can be transferred to the next-generation IC design.

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