Alpha-Particle and Neutron-Induced Single-Event Transient Measurements in Subthreshold Circuits

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Abstract—Experimental data from alpha particle, neutron, and heavy ion testing are discussed and analyzed from a subthreshold voltage SET characterization circuit. Using a Schmitt trigger inverter target chain fabricated in a 28-nm bulk CMOS process, SET pulse widths are captured from an operating voltage down to 0.32 V. These results show that energetic particles can induce SET pulse widths that range up to hundreds of nanoseconds when operating at voltages well below the nominal voltage. Additionally, the results show that sub-Vt circuits are significantly more susceptible, as compared to circuits operating at nominal voltages, to low-energy particles inducing SETs that have a high probability of being latched as errors in a combinatorial logic design.

Index Terms—alpha particles, radiation, single-event transients, soft errors, subthreshold

I. INTRODUCTION

Circuits that operate at voltages below the nominal voltage of the technology process are more susceptible to single-event effects (SEEs) than circuits that operate at nominal voltage. With the necessity to design circuits that operate at minimal voltages to conserve energy for space, medical, and Internet-of-Things (IoT) applications, circuits are increasingly operating at sub-threshold (sub-Vt) voltage levels. Previous work shows that single-event transient (SET) pulse widths increase with decreasing voltage [1-4], an issue that leads to a higher single-event error rate for low-power circuits compared to nominal-power circuits. With circuits operating at low voltages and an increase in sensitivity to energetic particles, it is necessary to understand the SET response of these circuits to allow designers to implement SEE mitigation schemes in the low-power circuits. While previous researchers have explored SEEs at sub-threshold voltage, very little prior work has presented direct measurements of SETs in a circuit designed specifically to operate at sub-threshold voltages. In this paper, we present direct measurements of SETs induced by alpha particles, neutrons, and heavy ions in a sub-threshold circuit fabricated in a standard 28-nm bulk CMOS process.

II. DESIGN OF THE SUBTHRESHOLD SINGLE-EVENT TRANSIENT CHARACTERIZATION CIRCUIT

The characterization circuits used in this work consist of three parts; the target, an OR-gate tree, and a level shifter as shown in Fig. 1. The target, which consist of 16 parallel chains of 100 Schmitt trigger inverters, and the 16-to-1 OR-gate tree operate at the desired testing sub-Vt voltage. Since the pulses generated by the targets at sub-Vt voltages tend to be very long, special high-speed measurement circuits are not required to record the SETs. The output pads on the chip are limited to pulses of widths greater than about 5 to 10 ns, therefore any pulse wider than that can be read directly from the chip.

The Schmitt trigger inverter, pictured in Fig. 2, is a unique inverter design that works well at ultra-low voltages. This is because the Schmitt trigger maintains a suitable on/off current ratio at lower voltages than a regular 2-transistor (2-T) inverter is capable of at equivalent voltages [5]. The feedback transistors, Mfp and Mfn, provide the mechanism to reduce the leakage currents by applying approximately 0 V across either M2 or M3, depending on the state of the inverter, giving the Schmitt trigger comparable switching performance at sub-Vt as a super-Vt regular inverter and superior noise margins at sub-Vt operation. For this reason, the Schmitt trigger is a good candidate for a sub-Vt SET measurement circuit as compared to a regular 2-T inverter.

At super-Vt operation, this operation manifests itself as a regular Schmitt trigger with hysteresis. Therefore, at regular voltage operation, a Schmitt trigger is designed to have a higher noise margin, compared to a regular inverter, effectively meaning the Schmitt trigger will filter out SETs. It’s for this reason, that other researchers have looked at using Schmitt trigger inverters to mitigate SETs [6-8]. However, if the Schmitt trigger is upset by an SET, the resultant pulse width is significantly longer because M3 and Mfn will both be on, reducing the effective pull-down current for the Schmitt trigger. This will be true for both super-Vt and sub-Vt operation.
This work is 2 µm² and the inverter-inverter spacing is approximately 1.1 µm.

Previous work on a Schmitt trigger SET characterization circuit used in this work was originally described with supporting simulations [13] and with data being presented on a 65-nm version of the test structure [14]. Due to the aforementioned high noise margin present in a Schmitt trigger inverter during super-Vt operation, SETs are not able to propagate in a Schmitt trigger above a certain voltage. However at sub-Vt operation, the SET widths can be very large. In this paper, we present the first data on alpha-particle and neutron-induced SET measurements in a 28-nm sub-Vt circuit, compare the SET widths to those induced by heavier ions, and finally compare the 28-nm data to the 65-nm data.

Another unique aspect of this work is that due the large SET widths present at subthreshold voltages and the addition of a level shifting circuit on our test chip, SETs can be measured directly without any special on-chip circuitry [15-16] or high speed cabling [17] as has been utilized in previous SET measurement studies.

III. ALPHA PARTICLE SET MEASUREMENT RESULTS

The Schmitt trigger inverter target circuit was exposed to alpha particles using a 0.1 µCi Polonium-210 (Po-210) source [18]. Po-210 emits alpha particles with an energy of 5.3 MeV and has a half-life of 138.4 days. For these experiments, the Po-210 source was simply placed on top of the exposed die of the test circuits and the alpha-particle induced SETs (which ranged from slightly less than 10 ns to over 200 ns) were captured on an oscilloscope. VDD was varied from 0.32 V to 0.5 V during the exposures. Over 1400 alpha-particle induced SETs were measured on three different parts and five different voltages over the course of several months of testing. Histograms of the alpha-particle induced SETs measured at full-width half maximum (FWHM) for four of the voltages are shown in Fig. 5.
A summary of the all alpha particle data taken on the test circuit is shown in Fig 6. The SET widths are plotted in a somewhat unique manner in this graph. In the plot, the red dot is the average SET width of all the measured SETs at the given voltage. The box represents the interquartile range of the measured SETs, and the notch in the box represents the median SET. Individual SETs measured outside the interquartile range are shown as individual points. The plot clearly shows that as VDD is raised, SET widths decrease. For example, at 0.5 V the alpha particle induced SET rate in the circuit is over an order of magnitude lower than the rate at 0.32 V.

To ensure that there was not a significant part-to-part variation in the alpha particle response or variability in the data due to how the alpha source was placed on top of the test chip, three different parts were tested. A summary of the data for three different parts tested at a voltage of 0.32 V is shown in Fig. 8. No statistically significant differences in SET widths and/or rates at which the SETs were generated were found between the three devices.

Another important aspect of SETs (and soft errors in general) is the rate at which they occur. In Fig. 7, the rate (i.e. the number of SETs normalized to the alpha particle fluence) at which alpha-particle induced SETs were measured is plotted as a function of VDD. As VDD is increased, not only does the width of the SETs decrease, the rate at which they occur also decreases significantly. For example, at 0.5 V the alpha particle induced SET rate in the circuit is over an order of magnitude lower than the rate at 0.32 V.

Figure 6. A one-plot summary of all of the SETs measured during alpha particle exposure on the 28-nm Schmitt trigger inverter test circuit. In this figure, the red dots represent the average, the notch is the median, the box is the interquartile range, and the points outside the box are individual SET points measured outside the interquartile range.

Figure 7. Rate at which SETs were observed during alpha particle tests. This figure shows that as the operating voltage is increased the number of measurable SETs decreases.

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Figure 8. SET measurements taken with a VDD of 0.32V on three different parts.

IV. NEUTRON-INDUCED SET MEASUREMENTS

Neutron exposure of the SET test circuit was performed at the Low Energy Neutron Source (LENS) at Indiana University [19]. At LENS a variable pulse, 13 MeV proton beam is used to generate neutrons up to an energy of 11 MeV. By adding or removing a polyethylene moderator in front of the device under test a large thermal neutron flux can be generated. Through the use of a remotely-controlled 1mm thick Cadmium cover, the thermal neutron flux can be effectively removed from the beam line. Testing for sensitivity to thermal neutrons at LENS is typically done by comparing the upset rate with and without the Cadmium cover [20-21].

The mechanism through which neutrons can induce an SET is different than with alpha particles and heavier ions. Neutrons do not directly generate electron-hole pairs. For fast neutrons, the ionizing particles are indirectly generated through a nuclear reaction with a material (most likely silicon) in the device. Thermal neutrons can create ionizing particles when they are captured by Boron-10. Boron-10 absorbs thermal neutrons and ejects alpha particles (Helium nuclei) via a $^{10}$B(n,α)$^7$Li nuclear reaction.

The SET circuit was tested with a VDD of 0.32V at LENS in the moderated beam with thermal neutrons and without. The SET widths measured under these two conditions are shown in Fig. 9. A total of 31 SETs were measured in the...
beam with thermal neutrons and 16 SETs were recorded in the beam with the same fast neutron fluence but with the thermal neutrons removed. This data suggests that at least some of the SETs measured were due to thermal neutron interactions. Due to the small sensitive volume of our target circuit (1600 inverters), extremely large fluences were needed to obtain these SETs. Due to this, we were not able to obtain better SET rate statistics during the neutron exposures. The differences in average SET width in Fig. 9 are most likely due to statistical error resulting from the small number of counts.

V. HEAVY-ION SET MEASUREMENTS

To further explore SET widths in this subthreshold circuit, the test structure was also exposed to heavy ions at the Texas A&M (TAMU) cyclotron facility. SETs measured with three different heavy ions (shown in Table 1) up to a linear energy transfer (LET) value of 26.6 MeV-cm²/mg. For comparison, the peak LET of an alpha particle is less than 2 MeV-cm²/mg. With an LET of 26.6 MeV-cm²/mg an ion will be generating over 10x more electron hole-pairs along its track than an alpha particle. A histogram of SET widths measured at 0.4V for the three ions is shown in Fig. 10, and the average SET widths obtained with Krypton at three different voltages are shown in Fig. 11. The interesting item to note is that the SET widths even with the much heavier ions are nearly the same as with alpha particles and neutrons. This effectively shows that once Schmitt trigger is upset, its slow response time at sub-Vt operation leads to long SET widths.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Energy (MeV)</th>
<th>LET (MeV-cm²/mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Krypton</td>
<td>1445</td>
<td>26.6</td>
</tr>
<tr>
<td>Argon</td>
<td>560</td>
<td>8.0</td>
</tr>
<tr>
<td>Helium</td>
<td>7</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Figure 9. SET measurements taken with a VDD of 0.32V at the IU LENS neutron source. 31 total SET were measured in the beam with thermal neutrons while only 16 SETs were measured to the same total fast neutron fluence with thermal neutrons removed.

Figure 10. Histogram of the SETs measured during heavy ion exposure on the 28-nm Schmitt trigger inverter test circuit operating at a VDD of 0.4V.

Figure 11. A one-plot summary of all of the SETs measured during krypton ion exposure on the 28-nm Schmitt trigger inverter test circuit.

Figure 12. 28-nm subthreshold SET cross section for a Schmitt trigger inverter vs. heavy ion LET for three different voltages.
The cross section per inverter for the 28-nm structure measured at the TAMU cyclotron for three heavy ions is plotted for several VDD values in Fig. 12. The cross section is simply the number of SETs measured divided by the ion fluence. The point of this figure is to show that the number of SETs measured decreases as VDD is increased and that the higher LET ions are able to induce more SETs.

VI. COMPARING 28-NM AND 65-NM SET WIDTHS

The average SET widths measured with krypton ions and alpha particles on the 28-nm test chip are plotted as a function of VDD in Fig. 13 and compared with the average alpha-particle SET widths taken on the 65-nm version of this SET circuit [14]. The 65-nm version of this circuit was constructed and tested in the same manner as the 28-nm version. Like the 28-nm test chip, the 65-nm test chip also consisted of long Schmitt trigger inverter chains connected to an on-chip level shifter that enabled SETs to be measured using an oscilloscope. The important takeaway from Fig. 13 is that the SET widths are about an order of magnitude shorter on average in the 28-nm circuit than in the 65-nm circuit.

![Figure 13. Average SET widths versus voltage for the 28-nm chip from exposure to alphas and krypton ions. Average SET widths from the 65-nm version of circuit are also shown.](image)

VII. CONCLUSIONS

An understanding of the susceptibility of sub-Vt circuits to energetic particles is important for multiple low-power applications. Alpha particle and neutron data shows that Schmitt trigger inverters operating below nominal voltage for a 28-nm bulk CMOS process can generate transients that range up to hundreds of nanoseconds in pulse width. Testing also affirms that SET pulse widths have an inverse relationship with the operating $V_{DD}$. Both heavy ion and alpha particle data show that SET pulse widths increase with decreasing $V_{DD}$.

Interestingly, the generated SET widths are roughly the same for an alpha particle and a heavy ion that deposits an order of magnitude more energy along its path. This effectively means that once enough charge is generated by a particle in the Schmitt trigger to change the state, the time it takes to restore the state is determined by the slow response time of the inverter.

The average width of the 28-nm SETs was about an order of magnitude smaller than the average SET width measured on a similar 65-nm circuit. The smaller SET widths along with the smaller transistor areas in advanced nodes bodes well for lower soft error rates in subthreshold circuits designed in advanced process nodes.

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