

ANTIFUSE FPGA FOR SPACE APPLICATIONS

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Abstract

This paper presents total dose and SEE testing data of recent antifuse products. It includes ONO-antifuse FPGAs: A1020B, A1020S, RH1020, A1280XL, A1460A, A14100A, A32140DX and A32200DX. Also included are preliminary results of pre-production metal to metal (M/M) antifuse FPGAs, the I100 and the RHI100. Finally, SEU rate calculations of Actel FPGAs are discussed.

I. INTRODUCTION

Among several FPGA (Field Programmable Gate Arrays) technologies, the antifuse FPGA has the major advantage for space applications because its programmable switch is immune to total dose effects [1].

Actel's ACT 1, ACT 2, and ACT 3 ONO (oxide-nitride-oxide) antifuse products have been very popular among space designers. However, until recently, Actel only offered commercial products with an extended screening process (MIL-STD-883B). The customer had to perform the radiation screening and then buy the tested lot. From a radiation tolerance point of view, this practice is essentially COTS (Commercial-Off-The-Shelf).

The recognition of the possibility of decreasing radiation tolerance for smaller device geometries in newer products prompted the pursuit of rad-hard technologies to ensure good radiation performance in future products. Two approaches were taken: we teamed up with a QML (Qualified Manufacturer List) rad-hard foundry to fabricate QML assured rad-hard products and a reputable radiation testing/analysis institute to test the pre-production products and to further improve the potentially rad-tolerant products by fine tuning the processing and circuit design.

Nevertheless, the central activity of rad-hard and rad-tolerant product development is radiation testing and analysis of the results. In this paper, we will present total dose and SEE (Single Event Effects) testing data of recent antifuse FPGAs. This is followed by SEU rate calculations.

II. RADIATION TESTING

TID testing was performed using a Cobalt-60 gamma ray source; rates ranged from 0.2-2 krad (Si)/hr. From our experience, applying dose in this range without annealing will generate more realistic and conservative testing results than those following the MIL-STD-883 method 1019.4, using dose rates between 50-300 rad (Si)/sec followed by 100 °C annealing to simulate space environment.

SEE testing used the Tandem Van de Graaff at Brookhaven National Laboratory and 196 MeV protons were at the Indiana University Cyclotron Facility.

Table 1 SEE Heavy Ions at BNL

Ion	Energy (MeV)	LET (MeV-cm ² /mg)
Cl-35	210	11.4
Ti-48	253	18.1
Ni-58	278	26.2
Br-79	286	37.2
I-127	320	59.7

Two series of device under test (DUT) designs are used for radiation testing; one for total dose tests and the other for SEE tests. The common root is the design for the A1020 series. Later DUT designs reflect the architecture and resource changes incorporated into later products.

For total dose, the 'TDxxxx' series is used, with the TD1020 being the base design used for all components. This tests logic gate functionality and propagation delay with strings of gates, some inverting. Flip-flops are incorporated to measure sequential structures including shift registers and counters using the majority of the device. Other DUT designs reflect the die being tested. For example, the TD1280 tests include I/O module latches. ACT 3 patterns, the TD1460 and TD14100 add tests for I/O registers, which are present in that architecture's I/O modules. Test structures are duplicated to permit testing of the new 'H-Clk' clock distribution system [2]. The TD32200 adds a built-in-test (BIT) section for performing self-tests of the embedded dual-port SRAM as well as a connector for the JTAG features [2].

For SEE, the TMRA1 is the base design for the A1020. This simple DUT matches the ACT 1 architecture and incorporates shift registers for testing C-module flip-flops as well as triple modular redundancy (TMR) structures for SEU immunity. Additionally, an internal buffer brings the clock distribution system off-chip to monitor for clock upset and aid in testing. The TMRA2 series is for ACT 2 devices. Here, distinctions are made in SEU performance for I/O-module latches, C-module (routed) flip-flops, and S-module (hard-wired) flip-flops. The ACT 3 designs add test support for the H-Clk as mentioned before and monitor the SEU performance of the I/O module registers. The TD32200 DUT was used for preliminary SEE testing for the A32200DX, with a variant ported to the A32140DX, and monitored embedded dual-port SRAM and control circuitry performance.

III. TOTAL DOSE CHARACTERISTICS

From previous characterization, the total dose tolerance of Actel's antifuse FPGAs are generally limited by the standby supply current, $I_{CCSTDBY}$. Usually this parameter will drift far out of specification long before functional failure occurs. For a preliminary evaluation, it is convenient to monitor, in situ, $I_{CCSTDBY}$. Defining a failure criterion by using this parameter is somewhat subjective. In this paper, we will try to present all plots for potential user discretion. We will use the point where $I_{CCSTDBY}$ is just out of its specification (20 mA) as the relative failure criterion, for the purposes of discussion.

A distinctive total dose failure mode due to the on-chip voltage converter (so-called charge pump) failure was also found by using a ground accelerated dose rate test. There is evidence showing that testing at lower dose rates may invoke this mechanism later than testing at higher dose rate [3].

The charge pump circuits provide an on-chip bias voltage higher than the external voltage supply, V_{cc} . As shown in Figure 1A, to pass a full logic '1' signal, a bias higher than V_{cc} is needed to fully turn on the gates of the N-MOSFET in the isolation circuit. This isolation circuit is turned off during the programming cycle, when voltages as high as 20 V are applied, to protect the logic circuitry in the module.

Total dose effects will degrade the charge pump voltage and reduce the passing of a logic '1' signal to less than V_{cc} . As shown in Figure 1B, the input buffer in each logic module will produce totem pole current if its gates are biased at a voltage less than V_{cc} . In this condition, the DUT power consumption quickly increases which is

observed as an exponential increase in current through the V_{cc} pins and the device functionally fails.

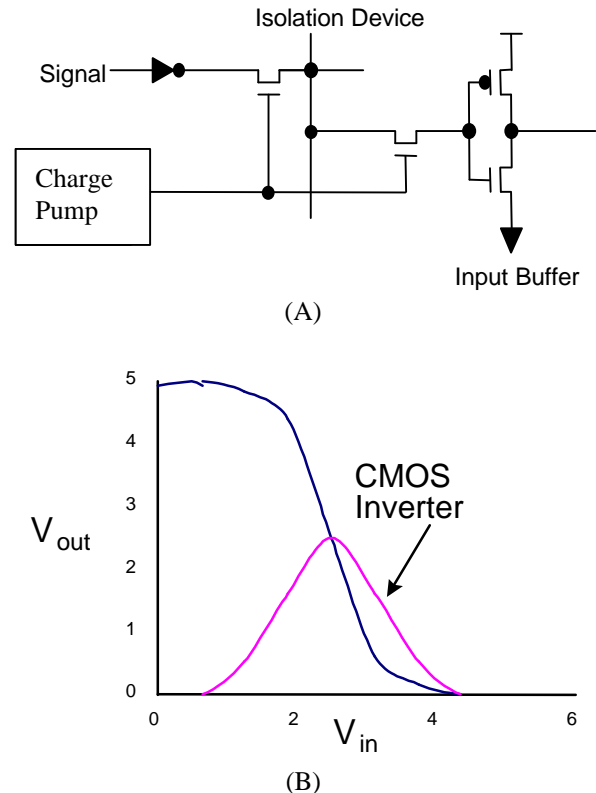


Figure 1 Charge pump failure mechanism

IV. RADIATION PERFORMANCE

The total dose and SEE testing results of some recent Actel products are presented here. Also included are testing results of two pre-production, soon to be released, new antifuse technology products.

A. A1020B/A1020S/RH1020

The 1020 family has been extensively tested. The A1020B is the latest version, which actually uses two technologies, 0.9 μm and 1 μm , which is transparent to the users. However, to date the best radiation performance A1020B device is the 1.0 μm die from MEC (Matsushita Electronics Corporation). A recent test of 1.0 μm A1020B from TI (Texas Instrument) shows a much lower latchup threshold, being around 22 MeV-cm²/mg. Since it has the same design and epi thickness as the same product from MEC, verified by destructive physical analysis (DPA), this reduced threshold cannot be easily explained, with further investigation needed.

The A1020S is a special lot, a hybrid with the 1.2 μm mask and design and the 1.0 μm processing technology. The idea is to continue the production of military-grade 1020's with the good total dose performance of the A1020A on a current 1.0 μm technology.

Figure 2 shows the plot of $I_{CCSTDBY}$ versus the accumulated total dose. It has the sudden peaking behavior that is characteristic of a charge pump failure [4]. $I_{CCSTDBY}$ went out of specification (20 mA) at 10 krad (Si), and reached 60 mA near the onset of the peak at 20 krad (Si). The charge pump failure was never observed in the A1020A when tested up to 100 krad (Si). The major attribute affecting the total dose sensitivity of the charge pump is the n-channel MOSFET threshold voltage (V_t), which is smaller in the 1.0 μm process. Further investigation and simulations are needed to elucidate the detailed mechanism.

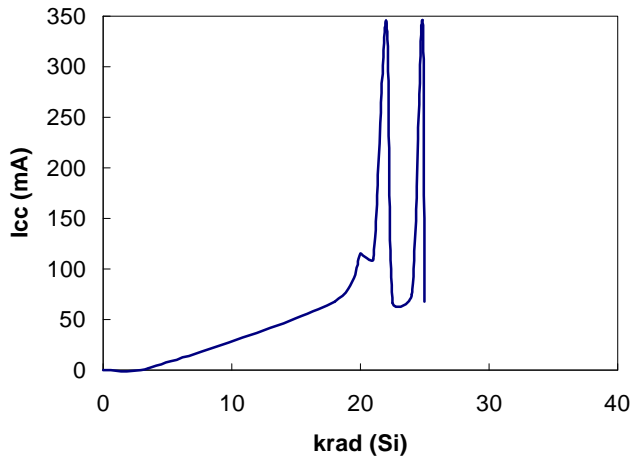


Figure 2 A1020S Total Dose Testing Results

The RH1020 is the QML rad-hard member of the 1020 series. The wafers are fabricated in a QML rad-hard, 0.8 μm processing technology (LMFS). The device geometries and die size are identical to the 1.0 μm A1020B. The RH1020 also has a different epi thickness, process steps, and high voltage transistor designs.

The RH1020's total dose performance should be the same as the RH1280's, and its SEE performance should be similar or better than the A1020B's. The major concern is that A1020B has a latchup threshold less than 50 $\text{MeV}\cdot\text{cm}^2/\text{mg}$. The first testing was to verify that the RH1020, with a thinner epi, has an acceptable latchup threshold. Due to test fixture limitations, the device was only tested normal to the heavy ion beam. No latchup was detected using Iodine with a LET = 60 $\text{MeV}\cdot\text{cm}^2/\text{mg}$.

B. A1280XL

The A1280XL is a pin-to-pin compatible part that replaces the older technology A1280 (1.2 μm) and A1280A (1.0 μm). It is manufactured using 0.8 μm and 0.6 μm technologies. However, unlike the A1280 and A1280A, this product does not use MEC as a foundry. The foundries used by Actel are Winbond (Winbond Electronics Corporation) and CSM (Chartered Semiconductor Manufacturing).

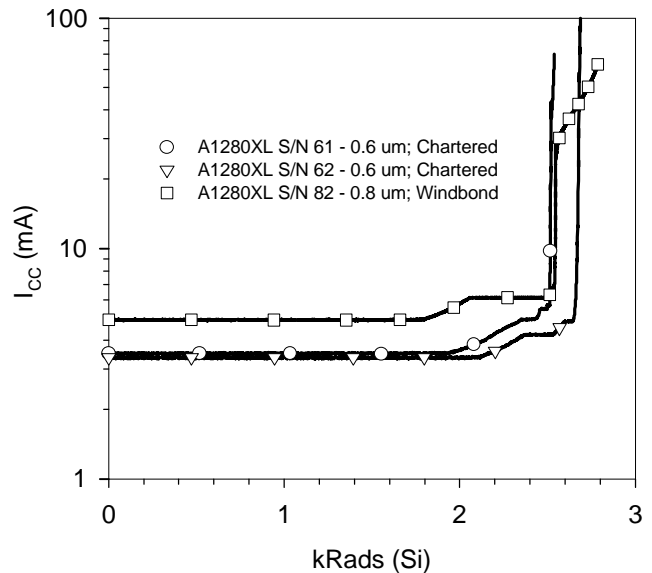


Figure 3 A1280XL proton testing results

Figure 3 shows results from total dose effect testing using a 196 MeV proton source at Indiana University. Different technologies (0.6 and 0.8 μm) from different foundries (Winbond and CSM) showed similar total dose performance levels. After about 2.5 krad (Si), there is functional failure caused by charge pump voltage degradation. For comparison, 1.0 μm A1280A manufactured by MEC often has tolerance > 10 krad (Si).

C. A1460A/A14100A

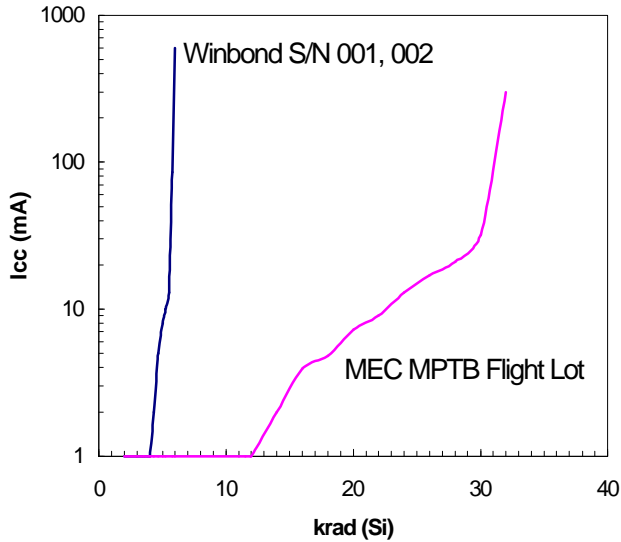


Figure 4 A1460A total dose testing results

These Act 3 'A' series devices are 0.8 μm CMOS technology, ONO antifuse products. Both the A1460A and the A14100A were tested for SEL. No latchup was detected for either product up to LET = 80 MeV-cm²/mg. Figure 4 shows typical gamma ray total dose testing results of Act 3 devices from Winbond and MEC. Winbond products have a much lower total dose tolerance, 6 krad (Si), than that of the MEC products, 28 krad (Si).

D. A32140DX/A32200DX

These two products belong to the A3200DX family and is the latest ONO antifuse product family. It is manufactured on a 0.6 μm CMOS process. Their new features are higher densities, dual-port SRAM (not available in 32140DX), wide decode circuitry, quadrant clocks, and JTAG [2]. This family uses Winbond and CSM foundries.

Figure 5 shows I_{CCSTBY} versus accumulated total dose. The current peak indicates a charge pump failure that starts at approximately 2.2 krad (Si). Heavy ion testing shows no latchup up to LET = 80 MeV-cm²/mg (Iodine).

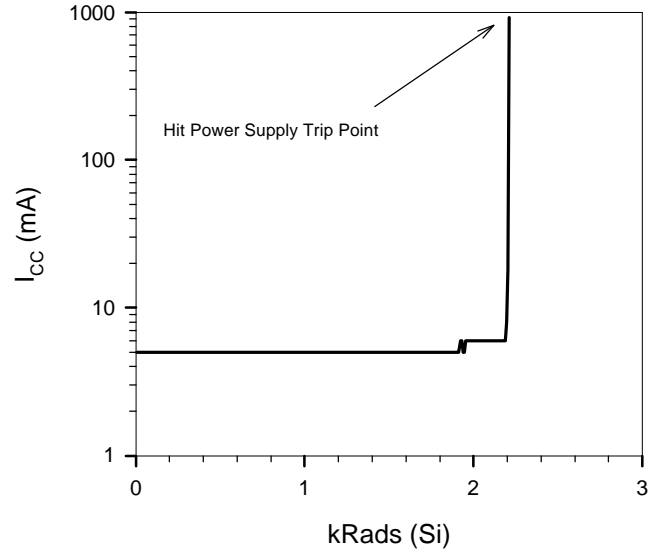


Figure 5 A32140A total dose (Cobalt-60) testing results

The A32200DX was found to latchup at LET \sim 11-16 MeV-cm²/mg. This latchup is most likely a result of the SRAM circuitry; the A32140DX and the A1280XL, having the same logic modules, do not latchup at LET > 80 MeV-cm²/mg. The layout design of SRAM does not implement a continuous guard ring structure at the n-well boundary.

E. I100/RHI100

These are pre-production products that implement new antifuse technologies and a new architecture. The I100 will be first introduced as a radiation tolerant product. It is manufactured on a 0.6 μm triple layer metal process at MEC. Its total dose and SEE effects are planned to be tested thoroughly before its introduction to the market. RHI100 is the rad-hard version of I100 and is to be manufactured on a QML rad-hard process in LMFS.

Some preliminary radiation testing results are presented here. Figure 6 shows I_{CCSTBY} versus total dose. Since this is a dual (3.3/5.0) VDC product, both power lines were monitored. From this figure, the total dose tolerance is 37 krad (Si) if 5.0 V VDC is applied, 53 krad (Si) if only use 3.3 V VDC. Figure 7 shows the total dose plot for the RHI100 and clearly demonstrates the rad-hard process - there was no I_{CCSTBY} change for either 5.0 V or 3.3 V line, up to 200 krad (Si). The experiment was stopped due to schedule constraint.

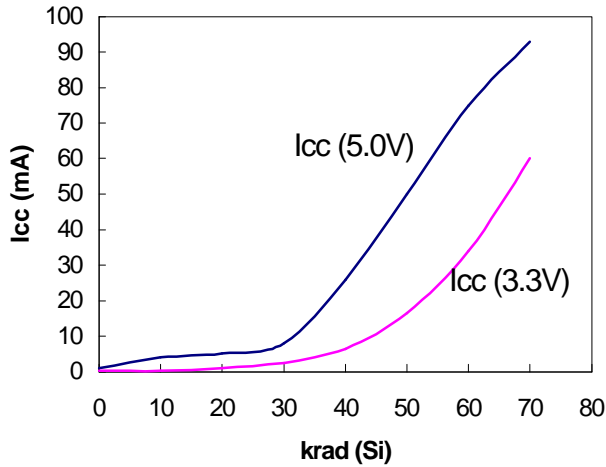


Figure 6 I100 total dose testing results

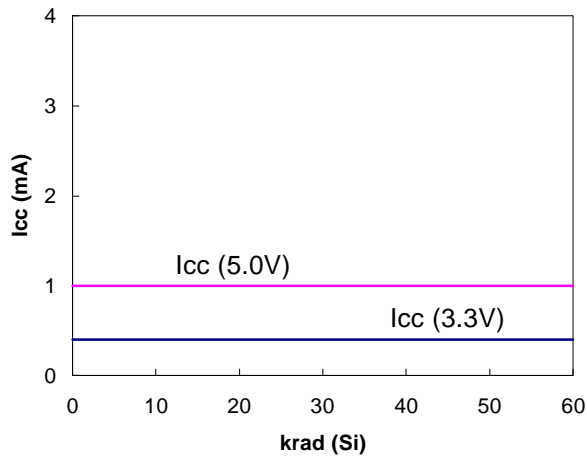


Figure 7 RHI100 total dose testing results

Figure 8 shows the SEU results for the I100 and the RHI100. Using $1 \times 10^{-7} \text{ cm}^2/\text{bit}$ criterion, the LET_{th} of the I100 is $17 \text{ MeV-cm}^2/\text{mg}$, and the RHI100 is $19 \text{ MeV-cm}^2/\text{mg}$. The saturation cross-section is $300 \mu\text{m}^2/\text{bit}$ for the I100, $150 \mu\text{m}^2/\text{bit}$ for RHI100. To explain the SEU difference between the two, we notice that the only significant difference between these two is that RHI100 uses an epi layer of $2 \mu\text{m}$ while the I100 uses $10 \mu\text{m}$. However, the mild difference indicates that most of the charges collected are near the surface.

SEL was not detected up to $80 \text{ MeV-cm}^2/\text{mg}$. SEDR was not detected up to $60 \text{ MeV-cm}^2/\text{mg}$ tested at zero tilting for the I100, with both voltage supplies set at their military-specified upper limits, 5.5VDC and 3.6VDC. This is a significant improvement compared to the ONO antifuse products which usually can be ruptured by heavy ions with $\text{LET} < 60 \text{ MeV-cm}^2/\text{mg}$.

Proton testing was also performed on the I100 using products from a different wafer fabrication facility in MEC, and no upset was detected when bombarded with 196 MeV protons. The dynamic I_{CC} is plotted versus total ionizing dose caused by protons (Figure 8). Using 20 mA criterion, the total dose tolerance is $> 50 \text{ krad (Si)}$.

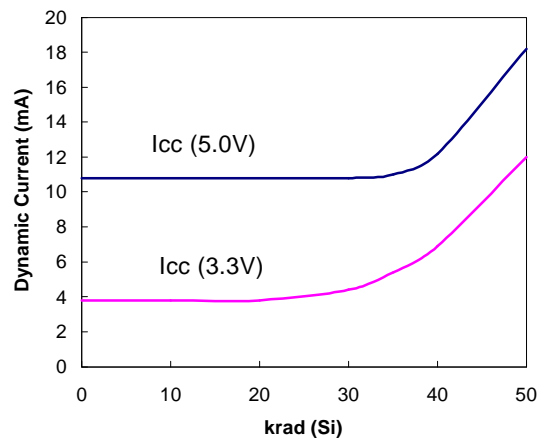


Figure 8 I100 proton testing results

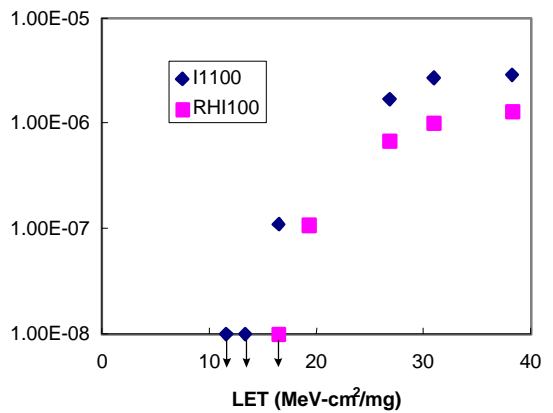


Figure 9 I100 and RHI100 SEU testing results

V. SEU RATE CALCULATIONS

As the use of COTS is gaining popularity, accurate SEU rate calculations are gaining importance because over conservative calculations will prohibit too many useful products from being used, resulting in a loss of performance and an increase in resources. Using just LET_{TH} and saturation cross-section will generate excessive upset rates for almost all the Actel's products.

The reason is that the SEU curve of Actel products usually possesses a smooth knee, which is the consequence of multiple active junctions with different critical upset charges in the latch/flip-flop.

A commercial software, Space Radiation, was used to calculate the galactic cosmic ray (GCR) SEU rates using the box approximation and curve fitting to a Weibull distribution with the A1280A used as an example. The orbit and space environment parameters (shown in Table 2) are those of a typical case for a GEO application.

Table 2 Space Radiation input parameters

Orbit	36,000 km, 0° inclination
Spacecraft Shielding	100 mil Aluminum
Earth Shadowing	Yes
Magnetic Weather	Stormy
Solar Cycle	Solar Min (1975, M=1)

Table 3 compares the calculated SEU rates between input 'Box Approximation' data using threshold LET and saturation cross section and Weibull fitting curves. An order of magnitude of error can result.

Table 3 Calculated SEU rates

Input Data	SEU Rates
Weibull Fitting	6.3×10^{-6} upset/bit-day
Box $LET_{th}=3.9\text{MeV}\cdot\text{cm}^2/\text{mg}$ Cross Section= $3.2 \times 10^{-6}\text{cm}^2/\text{bit}$	6.6×10^{-5} upset/bit-day
Box $LET_{th}=13\text{MeV}\cdot\text{cm}^2/\text{mg}$ Cross Section= $3.2 \times 10^{-6}\text{cm}^2/\text{bit}$	6.35×10^{-6} upset/bit-day

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