RADIATION TOLERANT ANTIFUSE FPGA

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Abstract-The total dose performance of the antifuse FPGA for space applications is summarized. Optimization of the radiation tolerance in the fabless model is the main theme. Mechanisms to explain the variation in different products are discussed.

I. INTRODUCTION

The antifuse FPGA (field programmable gate array) has become established as one of the favorite digital components for space-flight-electronics designers. The key advantage over other high-density programmable logic is the ionizing radiation tolerance of its programmable switch [1]. Substantial test data [1-3] indicates that an antifuse switch, either based on ONO (oxide-nitride-oxide) or MIM (metal-insulator-metal) technology, is immune to ionizing radiation, or total dose effects. Therefore, the total dose effects and hardening for an antifuse-based FPGA is determined by the technology on which its digital subsystem is based. In this case, it is CMOS technology.

CMOS technology for manufacturing digital systems has been aggressively scaled down during the last decade. To be competitive, the Actel antifuse FPGA has followed the same trend. We have to understand the implication of the CMOS scaling on the radiation response of the products, and subsequently improve their radiation tolerance. In the following sections, we will present an overview of Actel radiation tolerant products. Also included is a brief discussion of the future scaling and integration issues.

Before discussing the data and analyses, a brief history of Actel's "fabless" approach on radiation tolerant products is in order. As an IC manufacturer without a wafer fabrication facility, the development and improvement of total dose tolerance is under the constraints of the process availability and cost effectiveness of the foundry service. Due to the logistics and cost of this fabless approach, the total dose testing is more often performed at the product rather than device/wafer level. Fortunately, the intricacies of basic mechanisms of total dose effects on MOS devices have been extensively studied during the last few decades. Using well-known results in the published literature, all of the observed product behaviors due to ionizing radiation effects can be rationalized in the context of device physics and circuit theory. Therefore, process and design techniques can be applied to improve the radiation tolerance.

II. HISTORY OF SPACE FLIGHT PRODUCTS

Table 1 lists the Actel antifuse RT products offered to space-flight applications. Included are the commercial products from which the space-flight products are derived. The newer RTSXS family has the SEU hardened user register (or flip-flop), there is no commercial product that has the same design. However, from the user point-of-view, the products with the same numeric, for example A54SX32, A54SX32A, RT54SX32, or RT54SX32S, are equivalent when the Actel software and programmer is used for programming the intended digital designs.

Table 1 Radiation tolerant products and their commercial couterparts

Commercial Family	Commercial Product	Technology (feature size)	Vcc (volts)	RT/RH Derivative
ONO-Antifuse FPGA				
ACT1	A1020	2.0µm	5.0	
	A1020A	1.2µm	5.0	
	A1020B	1.0µm	5.0	RT1020 RH1020
ACT2	A1280A	1.2µm	5.0	RT1280A
	A1280XL	0.8µm	5.0	RH1280
		0.6µm	5.0	
ACT3	A1460A	0.8µm	5.0	RT1460A
		0.6µm	5.0	
	A14100A	0.8µm	5.0	RT14100A
		0.6µm	5.0	
MIM-Antifuse FPGA				
SX	A54SX16	0.5µm	3.3	RT54SX16
		0.35µm	3.3	
	A54SX16A	0.25µm	2.5	
	A54SX32	0.5µm	3.3	RT54SX32
		0.35µm	3.3	
	A54SX32A	0.25µm	2.5	
	A54SX72A	0.25µm	2.5	
RT only Family RTSXS		0.25µm	2.5	RT54SX32S
		0.25µm	2.5	RT54SX72S

Through the years, various users and Actel have evaluated the total dose performance of almost all the available antifuse products. Early 2 µm, 1.2 µm and 1.0 µm device were tested by interested users, notably the JPL report [4]. Due to the obsoletion of the older process (2.0 and 1.2 µm) and the softness of the newer product (e. g. 1.0 µm A1020B), in 1995 two products manufactured by radiation hardened foundry (now BAE Manassas), 0.8 µm RH1020 and RH1280

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were offered. However, due to cost, the radiation hardened foundry cannot offer state-of-the-art processing technology. To offer the whole range of advanced, high performance antifuse FPGA to space communities, in 1998 Actel started to offer radiation tolerant, RT products with lot-to-lot TID test data. There are two types of RT. A regular RT is a moderate modification of its commercial counterpart. There are 5 products in this type, RT1280, RT1460A, RT14100A, RT54SX16, and RT54SX32. Special RT, named as RTS, is a special design for space applications. The major design feature is the triple redundant latch to harden the SEU performance. The RTS total dose hardening is done by both the process and design techniques. There are two products in this type, RT54SX32S and RT54SX72S.

Table 2 Ionizing radiation tolerance of space-flight antifuse FPGA

Product	Technology	Foundry	V_{CC}	Tolerance (rad(Si))	
				I_{CC}	Func.
A1020	2.0µm ONO	MEC	5.0V	>100k	>300k
A1020A	1.2µm ONO	MEC	5.0V		>100k
A1020B	1.0µm ONO	MEC	5.0V	7k	20k
RH1020	0.8µm ONO	BAE	5.0V	300k	>1M
RT1020	0.8µm ONO	BAE	5.0V	300k	>1M
A1280A	1.0µm ONO	MEC	5.0V	5k	10k
A1280XL	0.8µm ONO	WIN	5.0V	2.5k	5k
RH1280	0.8µm ONO	BAE	5.0V	>600k	>1M
RT1280A	1.0µm ONO	MEC	5.0V	10k	20k
A1460A	0.8µm ONO	MEC	5.0V	10k	20k
RT1460A	0.8µm ONO	MEC	5.0V	20k	50k
A14100A	0.8µm ONO	MEC	5.0V	10k	20k
A14100A	0.8µm ONO	WIN	5.0V	5k	
RT14100A	0.8µm ONO	MEC	5.0V	20k	50k
A54SX16	0.5µm MIM	MEC	3.3V	50k	100k
RT54SX16	0.5µm MIM	MEC	3.3V	80k	150k
A54SX32	0.5µm MIM	MEC	3.3V	50k	100k
RT54SX32	0.5µm MIM	MEC	3.3V	80k	150k

Table 2 lists the typical total dose tolerance of the space-flight products. The RTS family is not listed because the test results are not finalized at this moment. Two tolerance numbers are listed, the tolerance for gross functional failure and I_{CC}. Since I_{CC} is the limiting factor for tolerance in every case here, it represents the electrical parameters. Variances such as lot-to-lot and dose rate are not considered here. Note also that these numbers come from test data. The product offering data are not exactly the same.

The tolerance dependence on the product, technology and foundry will be discussed in the following sections.

III. RT PRODUCTS AND FOUNDRY SELECTION

The space-flight application requires the immunity of single event latch-up (SEL), and this requirement is designed-in for RT products. To improve total dose performance, first we select the foundry and then harden the product.

Foundry MEC has been selected for the manufacturing of RT products. Table 2 shows that, excluding radiation hard foundry BAE, the product manufactured by foundry MEC is significant harder than that by WIN. For example, 0.8 µm A14100A by MEC is twice as tolerant as the similar device by WIN. In foundry MEC, the process leaves a unique layer in the field oxide. This layer pervasively covers the whole device. It acts as a block layer for the transport of holes to the Si/SiO_2 interface and also provides compensatory electron trapping to reduce the dominated hole trapping in the field oxide (see, for example, reference [5]). The parasitic leakage current induced by trapped holes at the interface is believed to be the cause of I_{CC} creeping out of the spec or the ultimate functional failure.

We provide lot-to-lot TID test data for RT products. The testing is basically following TM1019.5. The details are included in every report, and also can be found in reference [3].

IV. RT PRODUCT TOLERANCE AND HARDENING

From a product testing point-of-view, RT products, actually all antifuse FPGA, show their response to ionizing radiation mainly in three important parameters, gross functional failure, I_{CC}, and propagation delay. One of these three parameters is usually the limiting factor of the total dose tolerance.

For a DUT tested statically to functional failure, we always observed the occurrence of an abrupt I_{CC} change. In some devices, it is a pulse over time or total accumulative dose, and in other devices it is a steep cliff reaching half an amp at the peak. The behavior of this abrupt I_{CC} change with respect to total dose lead us to conclude that a charge pump circuit is the root cause of the functional failure.

The charge pump circuit is an on-chip DC-to-DC converter. It provides a voltage higher than V_{CC} on the gate of the isolation NMOS transistor. So they can pass V_{CC} signals without degradation. The isolation transistor functions as a turn-off pass gate to isolate high voltage programming voltage (typically > $2V_{CC}$) from low voltage (V_{CC}) transistors in the logic module.

Fig 1 shows the in-flux monitoring I_{CC} and charge pump voltage (V_{pump}) of a RT54SX16 device (V_{CC} = 3.3 V). The I_{CC} spike at approximately 55 krad(Si) coincides with the functional failure (in-flux functionality data not shown here). At this total dose, the charge-pump voltage significantly degrades from the initial 6 V to approximately 3.5 V. This V_{pump} drop is due to two causes. One is the radiation-induced reverse leakage in the NMOS diode of the capacitance-diode chain [6]. The other is the loading of the charge pump by

radiation-induced leakage current in the parasitic paths.

When V_{pump} drops some CMOS logic modules start to have floating nodes, and the ionizing radiation starts to charge these nodes and cause a transition current. In MIM products, as shown in Fig 1, only one transition peak is observed. In ONO products (Fig 2), multiple transitions are observed when functional failure occurs.
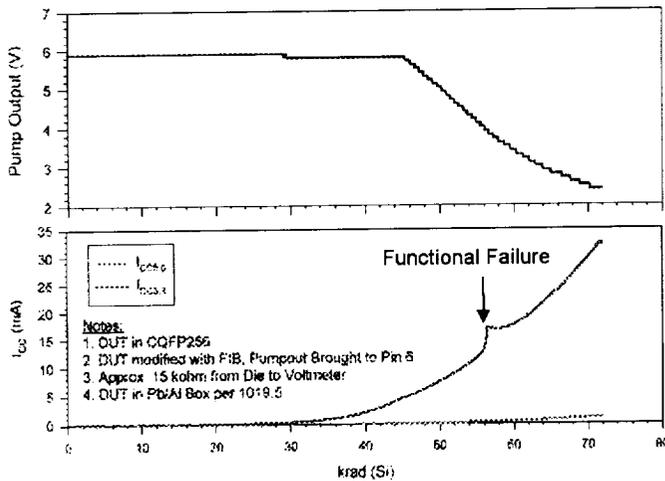

Fig 1   In-flux I_{CC} and charge pump voltage dependence of total dose of a RT54SX16 DUT [3], the occurrence of functional failure coincides with charge pump degradation

Propagation delay degradation was not an issue prior to 0.25 μm technology. It was always less than 5% up to the total dose right before functional failure occurred. For 0.25 μm RTSXS, however, we observed 10% degradation much earlier before DUT failing functional. Fig 3 shows the in-flux propagation dependence on the total dose. A RT54SX32S DUT from the first wafer lot was tested and analyzed. The root cause was found to be the same as the aforementioned functional failure, due to the charge pump degradation. After we re-designed the charge pump in RT54SX72S, the same measurement showed much less degradation. This same re-design is implemented in the current RT54SX32S device.

V. FUTURE TREND DUE TO TECHNOLOGY SCALING AND SYSTEM INTEGRATION

Table 1 shows a trend that as feature size and V_{CC} scales down, the radiation tolerance of the product increases. This trend is due to the scaling of the gate and field oxide thickness with the feature size, the increase of p-type doping in the channel and well for the NMOSFET [7], and the improvement of the interface quality of the gate oxide. The reduction of the gate oxide and field oxide thickness reduces the amount of oxide-trapped holes. The increase of the p-

type doping increases the threshold for the parasitic leakage paths, thus reducing the radiation-induced leakage current. As shown in Table 3, scaling increases the E-field of the gate oxide
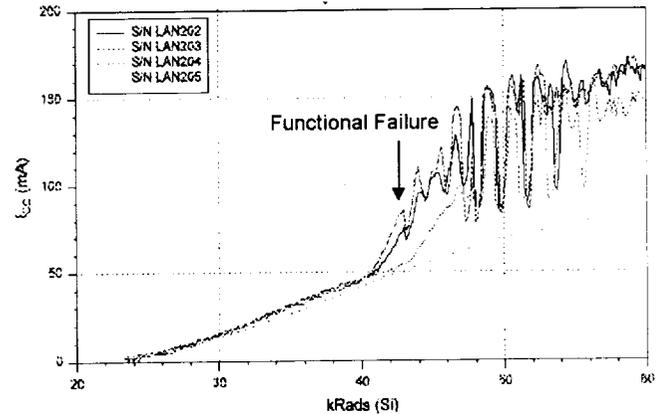

Fig 2   In-flux I_{CC} dependence of total dose of four A1460A DUT, I_{CC} "oscillates" after failing functionality
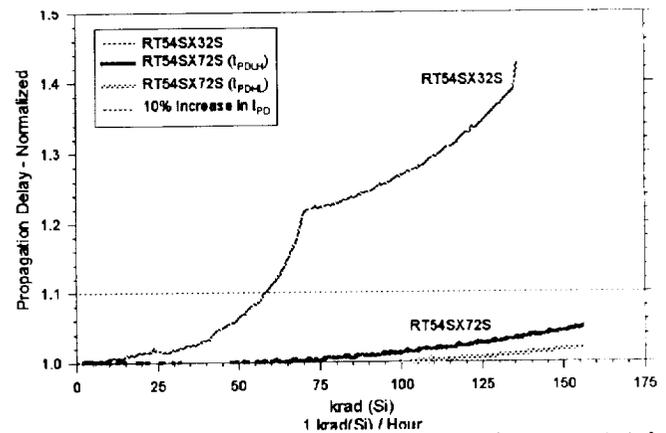

Fig 3   In-flux propagation delay dependence on total dose, RT54SX72S shows very small degradation after the charge pump been re-designed

significantly. To improve the oxide quality near and at the interface to prevent oxide breakdown, which actually is due to stress-induced trapped holes near the interface, thin oxide has to be manufactured by "radiation-hard" process [8]. The interface state at the Si/SiO$_2$ also has to be reduced to have a better control of the threshold voltage in thin oxides.

However the higher E-field in the thin gate oxide due to CMOS scaling should cause concerns for the radiation community. Single event gate rupture (SEGR) is exacerbated by high E-field. Total dose was suspected to enhance the susceptibility of SEGR. Although data showed that neither SEGR nor its total dose enhancement is an issue at present technology [9], we should still pay attention to it in the future scaling.

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Table 3 Gate oxide thickness and E-field in various technologies

Technology	V_{CC}	Gate Oxide	Oxide E-field
2.0µm ONO	5.0V	25nm	2.0MV/cm
1.2µm ONO	5.0V	25nm	2.0MV/cm
1.0µm ONO	5.0V	20nm	2.5MV/cm
0.9µm ONO	5.0V	20nm	2.5MV/cm
0.8µm ONO	5.0V	20nm	2.5MV/cm
0.6µm ONO	5.0V	15nm	3.3MV/cm
0.5µm MIM	3.3V	10nm	3.3MV/cm
0.35µm MIM	3.3V	7nm	4.7MV/cm
0.25µm MIM	2.5V	5nm	5.0MV/cm

The other thin oxide, high E-field issue is RILC (radiation induced leakage current). Its leakage mechanism is similar to SILC (stress induced leakage current), a better known phenomenon in reliability physics. Trap-assisted direct tunneling causes the leakage. In RILC, the traps are generated by the ionizing radiation. For 0.25 µm thick oxide, RILC is only observable when the total dose is above Mrad(Si) [10]. For thinner oxide and higher E-field, it is conceivable to occur at lower total dose exposures.

Future commercial antifuse FPGA will follow the SOC (system-on-chip) concept, integrating more and more high performance analog circuits, such as PLL (phase-locked loop) and LVDS (low voltage differential signal) with the digital modules. Conceptually, the ionizing radiation response of analog CMOS, increases with scaling. In order to extend RT products into this domain, great efforts will be needed.

VI. CONCLUSION

To provide state-of-the-art, high performance antifuse FPGA at a reasonable price, improving the radiation tolerance of products in a commercial foundry is a good, albeit compromised solution for space-flight applications. As the feature size scales, the scaled down V_{CC} improves the total dose tolerance of the CMOS digital logic. However, the critical supporting non-digital circuits such as the charge pump may become worse with the scaling. Proper engineering continues to be needed to apply radiation physics, device physics and circuit theory to enhance the tolerance of the future commercial products.

REFERENCES

[1] R. Katz, K. LaBel, J. Wang, B. Cronquist, R. Koga, S. Penzin, and G. Swift, "Radiation Effects on Current Field Programmable Technologies," IEEE Trans. Nucl. Sci. NS-44, 1945, (1997).

[2] J. Wang, B. Cronquist, B. Sin, J. Moriarta, and Katz, "Antifuse FPGA for Space Applications," RADECS 97 Data Workshop Record, p. 11, (1997).

[3] J. Wang, R. Katz, R. Koga, B. Cronquist, J. McCollum, and I. Kleyner, "Radiation Tests and Results of a Radiation Tolerant Antifuse FPGA, RT54SX," RADECS 2000 Workshop Proceedings, p. 253, (2000).

[4] M. Sandor, M. Davarpanah, K. Soliman, S. Suszko, and S. Mackey, "Field Programmable Gate Arrays: Evaluation Report for Space-Flight Application," NASA JPL Report, Sept. 12, 1992.

[5] I. Barchuk, V. Kilchitskaya, V. Lysenko, A. Nazarov, T. Rudenko, S. Djurenko, A. Rudenko, A. Yurchenko, D. Ballutaud, and J.-P. Colinge, "Electrical Properties and Radiation Hardness of SOI Systems with Multilayer Buried Dielectric," IEEE Trans. Nucl. Sci. NS-44, 2542, (1997).

[6] J. Wang, R. Katz, I. Kleyner, F. Kleyner, J. Sun, W. Wong, J. McCollum, and B. Cronquist, "Total Dose and RT Annealing Effects on Startup Tranisent in Antifuse FPGA," 1999 Fifth European Conference on Radiation and Its Effects on Components and Systems, RADECS 99, p. 274, (1999).

[7] J. Wang, R. Katz, J. Sun, B. Cronquist, J. McCollum, T. Speers, and W. Plants, "SRAM Based Re-programmable FPGA for Space Applications," IEEE Trans. Nucl. Sci. NS-46, 1728, 1999.

[8] I.-C. Chen, S. Holland, and C. Hu, "Electrical Breakdown in Thin Gate and Tunneling Oxide," IEEE Trans. Elec. Dev. ED-32, 413, (1985).

[9] F. Sexton, D. Fleetwood, M. Shaneyfelt, P. Dodd, G. Hash, L. Schanwald, R. Loemker, K. Krisch, M. Green, B. Weir, and P. Silverman, "Precursor Ion Damage and Angular Dependence of Single Event Gate Rupture in Thin Oxides," IEEE Trans. Nucl. Sci. NS-45, 2509, (1998).

[10] L. Larcher, A. Paccagnella, M. Ceschia, and Ghidini, "A Model of Radiation Induced Leakage Current (RILC) in Ultra-Thin Gate Oxides," IEEE Trans. Nucl. Sci. NS-46, 1553, (1999).

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