A 16 nm FinFET Radiation-hardened Flip-Flop, Bistable Cross-coupled Dual-Modular-Redundancy FF for Terrestrial and Outer-Space Highly-reliable Systems

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Abstract

A variation-tolerant and radiation-hardened flip-flop in a 16-nm FinFET technology called Bistable Cross-coupled Dual-Modular-Redundant Flip-Flop (BCDMR FF) was fabricated, which is an improvement on the BCDMR in 65 nm bulk. The 16 nm BCDMR FF exhibits cross sections below 1e-11 cm^2/FF at 0.8 V by Ag ions, which is 1/100 and 1/4,000 smaller than a conventional DFF in 16-nm FinFET and 65-nm planer processes respectively. With this low cross-section the BCDMR FF can be used for highly reliable and high performance systems.

I. Introduction

Our daily life relies heavily on the Internet. Due to this, network traffic is estimated to increase 1000x by 2020. This is a clear indication that 1000x the current robustness is mandatory for stable Internet connections in the near future. Aggressive process scaling has led to the prevalence of threshold voltage variations. While undoped channels in FDSOI or FinFET technology decrease process variations, robust circuit structures are still required to enhance yields, reduce production costs and improve reliability. Reliability and endurance are mandatory to products for network routers, automotive and aerospace.

This paper presents the design of a radiation-hardened flip-flop (FF) called Bistable Cross-coupled Dual-Modular-Redundant (BCDMR) [1], [2] fabricated in a 16 nm FinFET process. Results from heavy-ion, alpha particles, proton and neutron tests showed that the BCDMR in the 16 nm FINFET exhibits high radiation tolerance.

II. BCDMR FF

The schematic of BCDMR FF is shown in Fig. 1 (a) which is an upgrade of the Built-in Soft-Error Resilience (BISER) FF in Fig. 1 (b) [3]. Both of these FFs are radiation-hardened by keeping the correct values in dual-modular latches (ML0/1, SL0/1) and (weak) keepers (KM, KS). The C-element intercepts the transmission of a flipped value of the dual-modular latches. The BISER FF has several drawbacks: it is easily flipped by a single event transient (SET) pulse from the C-element and it is susceptible to process variations due to its weak keeper that must be asymmetrical to write a new value from the C-element. The BCDMR FF becomes robust to an SET pulse from C-elements by duplicating them. Even if an SET pulse flips a stored value in a keeper, the other C-element restores the stored value. Duplicated C-elements result in keepers with perfectly symmetrical structures and improve radiation hardness at higher frequencies of several hundred MHz [1]. It is also robust to process variations. The BCDMR FF in 65 nm has 45% smaller variations than the BISER FF [4].

TABLE I: Specifications of the fabricated chip and FFs.

Process	16 nm	65 nm [5]
Nominal Voltage	0.8 V	1.2 V
Die Size (mm^2)	2×2	6×6
# of BCDMR FFs	8,184	34,560
Area of BCDMR (μm^2)	4.96	24.3
Area of DFF (BCDMR/DFF)	NA	9.36 (2.6x)

BCDMR FFs in a 16-nm FinFET process were fabricated to determine its radiation hardness in the highly-scaled CMOS process. In Table I the specification of the fabricated chip and FFs are described. The area of the BCDMR FF in the 16 nm FinFET is 4.96 μm^2 which is 1/5x than that of 24.3 μm^2 in 65 nm. The BCDMR FF in 65 nm is 2.6× larger than a standard DFF.

The standard cell in 65 nm has an interleaved layout that puts distance between vulnerable components to prevent simultaneous flip of redundant components. The cell in 16 nm is not interleaved to increase the number of soft errors. It is possible to use commercial automatic place and routers for robust chips with the standard cells of the BCDMR FF.

III. Measurement Results and Discussions

Soft-error resilience of 16-nm BCDMR FFs were measured using neutron, heavy-ions, protons and α particle.

A. Neutron

In Table II and Fig. 2 spallation neutron beam results of BCDMR FFs fabricated in the 65 nm bulk [2] and the 16 nm FinFET are shown. The 16 nm BCDMR FF has the soft error rates (SER) of 13 and 6 FIT/MFF when CLK = 0 and 1 respectively. "Interleaved" means that redundant components of BCDMR such as latches, C-elements and keepers are placed far from each other not to flip simultaneously [2]. Two structures, interleaved (a) and non-interleaved ones (b) are depicted in Fig. 3. In Fig. 3 (b) all circuit blocks are placed similar to the schematic structure, while in Fig. 3 (a) the circuit blocks that cannot upset at the same time are placed as far as possible such as ML0 and ML1.

The SER of non-interleaved 16-nm BCDMR FF is equivalent to that in the interleaved one by 65 nm bulk. Terrestrial neutrons have broad energy spectrum to flip redundant components at the same time by a single particle hit. Thus,

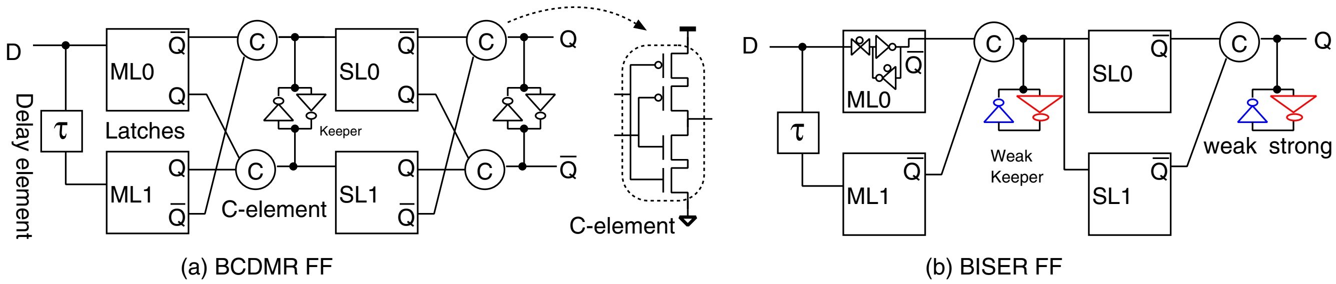

Fig. 1: Bistable Cross-coupled Dual-Modular-Redundancy (BCDMR) FF [1], [2] and BISER FF [3].

TABLE II: Neutron SER (Soft Error Rate) results of DFFs and BCDMR FFs in RCNP (65 nm) and LANL (16 nm). SER is in FIT/MFF.

Process	65 nm bulk			16 nm FinFET	
FF	DFF	BCDMR			
CLK	0, 1 (average)			0	1
Interleaved	-	No	Yes	No	
SER	554	50	9	13	6

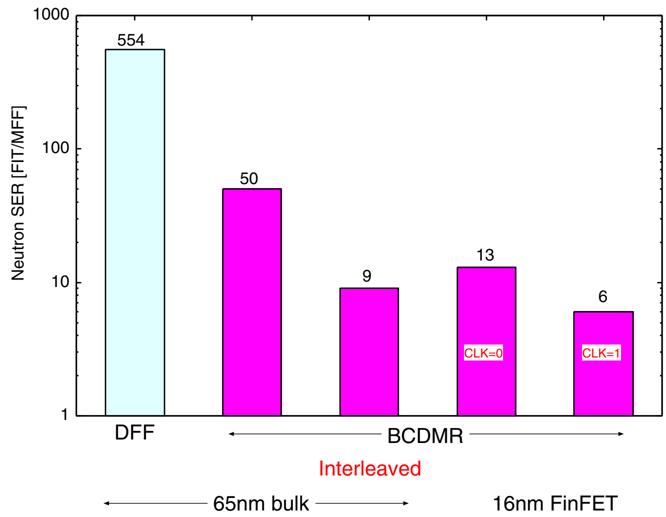

Fig. 2: Neutron SERs.

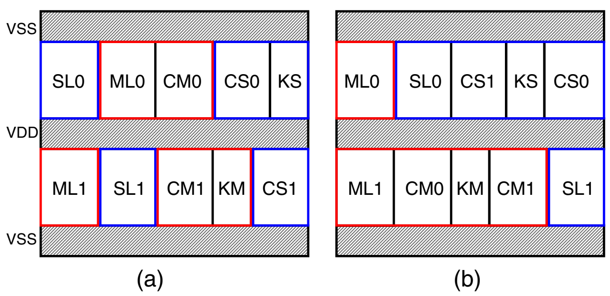

Fig. 3: Interleaved (a) and non-interleaved (b) floorplans of BCDMR.

interleaved layouts in 16 nm must decrease SER as same tendency as in the 65 nm bulk results.

B. Heavy Ions

High energy particle activity of heavy ions is shown in Tables III. In Fig. 4 the cross sections (CS) derived from

TABLE III: Irradiated heavy ions in the Berkeley Lab. for 16 nm FinFET in QST TIARA for 65 nm. LET is in MeV-cm^2/mg.

Facility	Berkeley Lab.			TIARA		Berkeley Lab. [6]	
Ion	Cu	Kr	Ag	Ar	Kr	Kr	Xe
LET	21.2	30.9	46.8	15.8	40.3	25.0	49.3

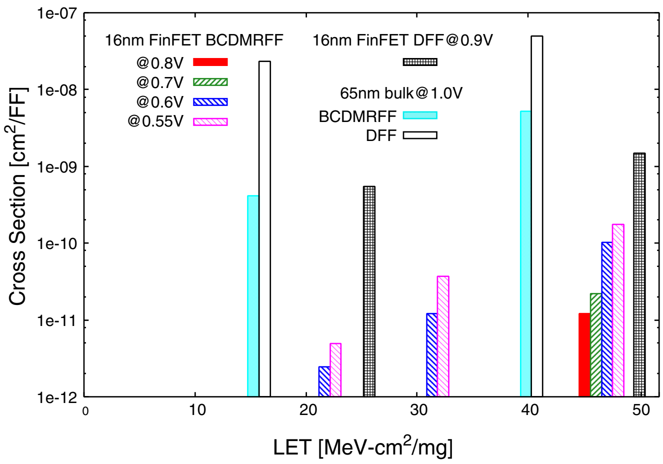

Fig. 4: Heavy-ion-induced soft error cross section. 16 nm FinFET DFF is from [6].

heavy ion testing of perpendicular hits of the BCDMR FFs are plotted with conventional DFFs [6]. There is no error in 16 nm FinFET BCDMR FFs by lower energy ions below Ar (LET = 9.74 MeV-cm^2/mg). In the 65 nm bulk process, the CS of a conventional FF by Kr ions (LET = 40.3 MeV-cm^2/mg) is 5.22e−08 cm^2/FF which is 10× larger than 5.25e−09 cm^2/FF of the BCDMR FF. The CS of the BCDMR FF in 16-nm by Ag ions (LET = 46.82 MeV-cm^2/mg) at 0.8 V is 1.22e−11 cm^2/FF which is 1/400 smaller than that of the BCDMR FF by Kr ions (LET = 40.3 MeV-cm^2/mg) in the 65 nm bulk. Thus the BCDMR FF in 16 nm is approximately 4,000× (= 10×400) stronger than the DFF in the 65 nm bulk. The CS of 16 nm BCDMR FF at 0.8 V and Ag ions is 1/100 smaller than that of the 16 nm conventional FF at 0.9 V and Xe ions [6]. It is sufficiently enough to support the estimated increase in network traffic expected by 2020.

In outer space, heavy ions hits on silicon from any angles. FinFETs tend to more sensitive to a horizontal hit than a vertical one because of their 3D structures. In Fig. 5 CS from angular dependencies are shown. The BCDMR FF in 16 nm has smaller CS below 1.0e−12 cm^2/FF by ions from 30 and

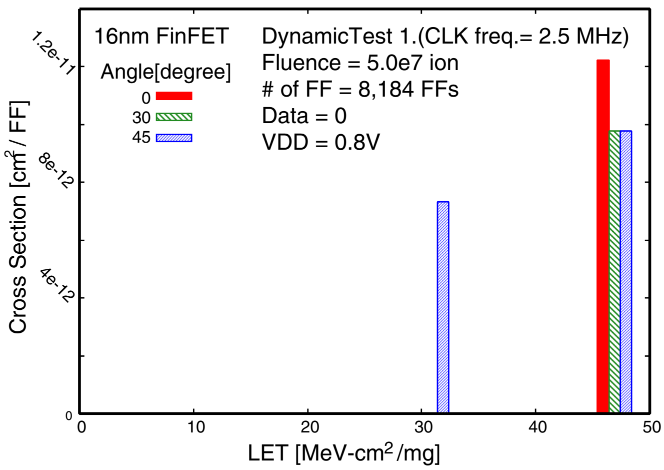

Fig. 5: Angular dependence.

TABLE IV: Comparison of cross sections of FFs fabricated with a 28 nm [7] and BCDMR FF in 16 nm FinFET. CS is in cm^2/FF.

	Area	CS by LET (MeV-cm^2/mg)	
28 nm [7]	(a.u.)	14.59	58.78
DFF	1.0	1.5e−09	4.0e−09
Redundant FF	∼2.6	6.0e−11	2.0e−09
LEAP	∼2.6	1.0e−11	2.0e−11

16 nm	Area	CS by LET (MeV-cm^2/mg) at 0.8 V	
	(μm^2)	30.86	46.92
BCDMR	4.95	0	1.22e−11

45 degrees. The BCDMR FF exhibits similar CS for all angles because of the low possibility for a heavy ion to go through its redundant components at the same time.

CS with redundant FFs in [7] are compared in Table IV. The CS of the redundant FF becomes large at the higher LET of 58.78 MeV-cm^2/mg, which is caused by Multiple Cell Upsets (MCU) of redundant components. The LEAP technology [8] mitigates MCUs by optimizing layout structures without redundancy. But LEAP must pay almost same amount of area penalty as the redundant FFs. The BCDMR FF in 16 nm has equivalent CS with LEAP. Suppression of MCUs becomes better by interleaving layout components.

C. α and Proton

Beam-test setups and results by α and proton is shown in Table V. The 16-nm BCDMR FF achieves a low error count of 10 in α and the CS of 1.43e−13. If the alpha fluence of 0.002 cph/cm^2 [9] is assumed by low-alpha material, the SER becomes less than 1 FIT/MFF. In [10], α emissivity values from solder bumps are distributed from 1e-3 to 1e-1 cph/cm^2. No errors in proton tests as can be seen in the bottom of Table V.

IV. Conclusions

The BCDMR FF fabricated in a 16-nm FinFET process exhibits higher radiation hardness by neutron, heavy ions, α and proton tests. The SERs by spallation neutron tests are 13 and 6 FIT/MFF when CLK = 0 and 1 respectively. The cross section by heavy ions are 1e−11 cm^2/FF by Ag ions (LET = 47 MeV-cm^2/mg). It is 1/100 lower than a conventional D-FF in 16 nm FinFET. The SER from α particles is less than

TABLE V: Beam-test setups and results by α and protons.

	α	proton
Source	^{241}Am	TRIUMF
Energy [MeV]	N/A	105
Fluence [/cm^2]	8.52×10^9	1.33×10^{12}
Vdd [V]	0.85	0.80
Data	All0	
Clock [MHz]	2.5	
Error Count	10	0
CS [cm^2/FF]	1.43×10^{-13}	0

1 FIT/MFF if the alpha fluence of 0.002 cph/cm is assumed. There is no error in proton tests. The BCDMR FF can be used for terrestrial and outer space products such as automotive and satellites.

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