

A New Method for Mitigation SEU Errors in Three-Dimensional FPGAs

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ABSTRACT: Now a day's one of the most crucial issues in the field of FPGAs, especially in SRAM FPGAs is single event upsets. One of the most effective methods to decrease these errors is using three dimensional FPGAs. This paper presents evaluation and mitigation of SEU cost on six layers three-dimensional (3D) FPGAs. The evaluation results show that SUE rate decrease about 67% on six layers 3D FPGAs. We also estimate the SEU cost improvement due to changing the place of 6 layers on 3D FPGAs, and it shows 28% improvements. However because of the importance of Trough Silicon Vias (TSVs) on delay estimation, we tried to make a trade-off between total TSV length and SEU costs.

KEYWORDS: Single Event Upset (SEU), Three-dimensional FPGAs, Total TSV length.

I. INTRODUCTION

A field programmable gate array (FPGA) is a flexible and reusable design alternative to costume integrated systems. The basic FPGA architecture consist of symmetrical array of user-configurable logic blocks and reprogrammable interconnections, which consist of wire segments and switch boxes [2], [3]. However this flexibility often comes with substantial performance cost. And on the other hand interconnect delay causes FPGA speed to be slower than the other ASIC designs for the same circuits [4], [8].

Another issue in field of field programmable gate arrays is soft errors. Soft errors which was a concern for space application in the past, become a concerning issues at ground level. Alpha particles and atmospheric neutrons cause single-event upset (SEU). Nowadays one of the most important concerns on FPGAs is these single events upsets [5]. Recently the concept of three-dimensional FPGAs was proposed with the idea of overcoming all these issues. 3D FPGAs replace a lot of long interconnections with short interconnects. And also provide layered architecture, which is useful to overcome SEU issues [6].

This paper considers the modelling and evaluation in [1], and proposed new layered placement to improve SEU cost, and also proposed a trade-off between total TSV length and SEU costs. The experimental results show that by means of six layers 3D systems, we can reduce SEU cost up to 73%. This improvement can be achieved, since the SEU effects are limited on middle layers of 3D FPGAs. In our studies we compare four layers and six layers 3D FPGAs. Also we improve SEU cost on 3D FPGAs by changing the place of most SEU affected layers, so we improve 3D FPGAs SEU cost up to 28%.

Paper is organized as follows. Section II describes the different method of evaluation and mitigation of SEU errors by means of CAD algorithms. Section III describes SEU on FPGAs. Section IV discusses evaluation and mitigation of SEU in 3D FPGAs. Section V presents the experimental results. Finally, last section concludes the paper.

II. RELATED WORK

Up to now there are many different studies in this field, which mitigate SEUs with the means of CAD algorithms. One of the studies is [9], a new reliability oriented place and route algorithms, based on using triple modular redundancy

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(TMR). Although TMR technique decreases the SEU effects significantly, but it causes high performance at the same time.

Another research in this field is [7], which mitigates SEUs by means of placement and routing algorithms. In that paper the VPR tool is modified so that placement and routing are used but the algorithms are SEU avoidance.

The other work in this field is [1], which is used the VPR and TPR placement algorithms to evaluate SEU errors on three dimensional FPGAs. In this work, they used the SEU errors equations for conventional FPGAs and extend it for three dimensional FPGAs.

III. SEU IN FPGAS

Nano metric technologies are sensitive to radiation that may happen both in space environment and at the ground level. Soft errors which was a concern for space application in the past, become a concerning issues at ground level. Alpha particles and atmospheric neutrons cause single-event upset (SEU). Neutrons create soft errors in an indirect manner. A high energy neutron may interact with silicon, oxygen, or other atoms of chip. Thermal neutrons may also cause soft errors. In storage cell (memory cells, flip-flops, and ...), a strong pulse will reverse the cell state. And it will cause Single Event Upset [5]. This is one of the most popular soft errors. Unfortunately, packaging couldn't effectively solve this problem. Since SEUs are made of neutrons which pass through packaging easily. Nowadays one of the most important concerns on FPGAs, especially SRAM FPGAs, is these single events upsets. So our circuits should be aware of these errors.

One of the most practical methods of evaluation SEU costs is mentioned in [7] that evaluate SEU rate by means of placement the FPGAs components. The effects of SEU on FPGAs routing resources can be classified like this: Short fault, Open fault, Bridging fault.

They use this metrics to evaluate the SEU cost like this:

$$\text{SEU Cost} = \alpha \cdot \text{Short Fault Cost} + \beta \cdot \text{Open Fault Cost} + \delta \cdot \text{Bridging Fault Cost} \quad (1)$$

Where the three different types of SEU cost component can be controlled by user defined α , β , and δ . But in this study we consider all these three multiplications the same. The short fault cost should be defined in a way that the numbers of programmable switches causing a short to non-usage nets decrease. So by means of Eq. (2) we decrease the nets' length inside of the FPGA. We use the following Eq. to determine the short fault cost in our study:

$$\text{Short Fault Cost} = \sum_{i=1}^{N_{nets}} q(i) \cdot [bb_x(i) + bb_y(i)] \quad (2)$$

Where N_{nets} shows the number of nets, $q(i)$ is used to determine the net terminal numbers, $bb_x(i)$ and $bb_y(j)$ are x and y dimensions of bounding box of net i. For open fault cost again they consider nets' length, because in short wires the probability of open faults is very low. So for open fault cost again we use Eq. (2).

For bridging fault cost we should consider the overlapping between the bonding boxes of two nets. And the common region between every two nets bonding boxes should be decreased. This can be defined by Eq. (3):

$$\text{Bridging fault cost} = \sum_{i=1}^{N_{nets}} \sum_{i \neq j, i \neq j}^{N_{nets}} q(i) \cdot q(j) \cdot cbb_x(i, j) + cbb_y(i, j) \quad (3)$$

Where $q(i)$ and $q(j)$ are the number of terminals for net i and net j, respectively. $cbb_x(i, j)$ and $cbb_y(i, j)$ are the common x, y dimensions of the overlapping area of the bonding boxes of net i and j.

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IV. EVALUATION AND MITIGATION OF SEU IN 3D FPGAS

The extended model of SEU cost for three dimensional FPGAs is proposed in this section. Then we use these equations to compare the SEU rate on four and six layers 3D FPGAs.

As we mentioned before in [7] there is a SEU cost equation, which they use it to make VPR tools, SEU aware. This equation consists of three elements, short fault cost, open fault cost, bridging fault cost. In [1] we extend this equation for evaluating the SEU cost on three-dimensional FPGAs. Where the three different types of SEU cost component can be controlled by user defined α , β , and δ . But in this study we consider all these three multiplications the same. The short fault cost should be defined in a way that the numbers of programmable switches causing a short to non-usage nets decrease. So by means of Eq. (4) we decrease the nets' length inside of the FPGA. We use the following Eq. to determine the short fault cost in our study:

$$3DSFM = \sum_{l=1}^{N_{Layers}} DF(l) \cdot \sum_{i=1}^{N_{nets}} q(i) \cdot [bb_x(i) + bb_y(i)] \quad (4)$$

Where N_{Layers} is the number of 3DFPGAs layers, and $DF(l)$ is the multiplication that shows Neutron effects in each layer.

As mentioned in [6] depth of Neutron electron holes on Silicon is about $5.3\mu\text{m}$, and it shows that the central regions of ICs are somehow the most safety regions. So we allocate lower multiplications to the central layers. And from the central layers to the first and last layer, this multiplication is decreased. In this paper without considering the substrate effect, the same multiplications are allocated to the first and last layers. Since, we may use these ICs, out of the earth atmosphere.

For open fault metrics (OFM), we use the same equation with short fault metrics (SFM). Because in both of them interconnect length play the most important role for evaluations.

For bridging fault cost, we use Eq. (3), which mentioned in the previous section. And we extend it like this:

$$3DBFM = \sum_{l=1}^{N_{layers}} DF(l) \cdot \sum_{i=1}^{N_{nets}} \sum_{j=1, j \neq i}^{N_{nets}} q(i) \cdot q(j) \cdot [cbb_x(i, j) + cbb_y(i, j)] \quad (5)$$

At last with replacing the above value in the proceeding equation, we can evaluate the total SEU costs.

$$SEU \text{ Metric} = \alpha \cdot 3DSFM + \beta \cdot 3DOFM + \delta \cdot 3DBFM \quad (6)$$

For evaluating SEU metrics in conventional FPGAs, VPR routing file is used. And for three dimensional FPGAs, TPR routing file is used. However, TPR is designed for placement and routing three dimensional FPGAs.

In this paper we proposed a new model for improving the SEU metrics in three dimensional FPGAs. In this method we replace the most SEU affected layers with central layers. Since neutron electron holes is limited at the central layers, as mentioned before. In this way we allocate the lower multiplication for these layers.

Then we use the Z parameters, which is used in channel z of TPR routing files, to determine the number of TSVs between each two layers. Though with the advent of total TSV length and SEU metrics, we proposed a trade of between them. First of all we evaluate the SEU metrics for any kind of layers placement, by means of Eq. (4, 5, and 6). On the other hand by means of number of TSV between each two layers, we determine the total TSV length for each type of layers placement. At last we use Eq. (7), which mentioned below, to calculate the minimum product of these two criteria.

$$\text{Cost} = \text{Total TSV length} \times SEU \text{ Metric} \quad (7)$$

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Optimization of this parameter is important for us, because, having the minimum SEU metrics is our main goal. And on the other hand minimum total TSV length cause minimum propagation delay. Reducing propagation delay is really important in the industry, and with this optimization, we achieve this goal.

V. EXPERIMENTAL RESULTS

In order to evaluate the result of this technique, we have applied this algorithm to 10 MCNC benchmarks. We use the VPR and TPR routing files of these benchmarks to compare SEU metrics on conventional FPGAs and 4 and 6 layers three dimensional FPGAs.

It is important to mention that, we have done this experiments under the condition that, there isn't any thermal issue for three dimensional FPGAs, if we consider the thermal issues, the results may be different. On the other hand, we do not change the architecture of TSVs, and the placement of TSVs is the same as what the TPR designed.

We use MCNC benchmarks to create the TPR routing files for six layers three dimensional FPGAs. Then we evaluate SEU metrics for six layers 3D FPGAs. The results of this experiments are compared with four layers 3D FPGAs and conventional FPGAs. You can see the experimental result on table 1. As mentioned before because open fault metrics and short fault metrics are somehow the same, we don't show open fault metrics in our tables. As you can see in table 1, the SEU metrics on six layers 3D FPGAs improved up to 73% in comparison with conventional FPGAs. So we can conclude that three dimensional integration, with more layers can optimize SEU costs on field programmable gate arrays.

TABLE I: SEU ERROR METRIC IN 2D AND SIX LAYERS 3D FPGAS

BM	2D FPGA			6 LAYERS 3D FPGA			SEU IMPROVEMENT (%)
	SFM	BFM	SEU	SFM	BFM	SEU	
ex5p	137,920	176,800,676	177,076,516	197,023	52,970,096	53,364,142	69.86
alu	260,826	447,715,466	448,237,118	313,463	100,355,892	100,982,818	77.47
dsip	338,150	536,664,124	537,340,424	284,835	79,975,899	80,545,569	85.01
seq	248,737	393,534,358	394,031,832	375,131	136,869,344	137,619,606	65.07
des	231,010	216,576,942	217,038,962	287,992	66,632,391	67,208,375	69.03
bigkey	292,311	445,656,527	446,241,149	320,864	90,368,906	91,010,634	79.61
diffeq	150,638	202,682,718	202,983,994	225,398	54,550,321	55,001,117	72.90
frisc	562,197	1,484,057,425	1,485,181,819	831,883	524,630,873	526,294,639	64.56
elliptic	615,138	2,051,473,413	2,052,703,689	858,897	556,927,722	558,645,516	72.78
tseng	93,827	97,820,427	98,008,081	138,851	25,087,134	25,364,836	74.12
Average	293,075	605,298,208	605,884,358	383,434	168,836,858	169,603,725	73.04

We mentioned that due to the limitation of, depth of neutron electron holes on silicon the central layers on 3D FPGAs are the safety regions. First of all, we use Eq. (4 and 5) to determine short fault metrics, and Bridging fault metrics with the same multiplications. Then we use Eq. (6) to evaluate the SEU metrics on each layer, and compare all of them. At last, we change the place of layers with highest SEU metrics to the central layers. And we allocate lower multiplications to them. After finding the most optimized layers placement, we evaluate the optimized SEU metrics. Tables 2 and 3, respectively shows the comparison of SEU metrics in worst and best case, between six and four layers 3D FPGAs. 28% SEU metrics optimization, convinced that optimized layer placement, has great effect on 3D FPGAs SEU metrics. Of course to getting this optimization, we cost a lot. Total TSV length is one of those costs that we suffer to achieve lower SEU metrics. To evaluate this cost, we use channel z on TPR routing files to determine the number of TSVs between each two layers, and then with means of each two layers distances, we evaluate the total TSV lengths.

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TABLE II: SEU ERROR METRIC MITIGATION ON FOUR LAYERS 3D FPGAS BY LAYER ASIGNMENT

BM	4LAYERS 3D FPGGA SEU METRICS BEFORE LAYER ASIGNMENT			4LAYERS 3D FPGGA SEU METRICS AFTER LAYER ASIGNMENT			SEU IMPROVEMENT (%)		
	SFM	BFM	SEU	SFM	BFM	SEU	SFM	BFM	SEU
ex5p	212,588	79,741,634	80,166,810	153,625	55,551,978	55,859,228	27.74	30.34	30.32
alu	352,358	179,254,526	179,959,242	264,481	129,769,781	130,298,743	24.94	27.61	27.60
dsip	322,640	131,356,780	132,002,060	239,998	93,194,830	93,674,826	25.61	29.05	29.04
seq	437,576	240,475,468	241,350,620	323,664	175,303,466	175,950,794	26.03	27.10	27.10
des	331,180	112,097,024	112,759,384	284,313	81,989,250	82,557,876	14.15	26.86	26.78
bigkey	378,452	162,345,076	163,101,980	334,076	116,950,262	117,618,414	11.73	27.96	27.89
diffeq	274,150	102,312,984	102,861,284	202,305	74,985,212	75,389,822	26.21	26.71	26.71
frisc	940,008	849,418,096	851,298,112	696,040	619,108,830	620,500,910	25.95	27.11	27.11
elliptic	998,252	970,851,462	972,847,966	730,312	696,518,978	697,979,602	26.84	28.26	28.25
tseng	154,774	37,436,440	37,745,988	111,599	25,595,557	25,818,755	27.90	31.63	31.60
Average	440,198	286,528,949	287,409,345	334,041	206,896,814	207,564,897	23.71	28.26	28.24

TABLE III: SEU ERROR METRIC MITIGATION ON SIX LAYERS 3D FPGAS BY LAYER ASIGNMENT

BM	6 LAYERS 3D FPGGA SEU METRICS BEFORE LAYER ASIGNMENT			4LAYERS 3D FPGGA SEU METRICS AFTER LAYER ASIGNMENT			SEU IMPROVEMENT (%)		
	SFM	BFM	SEU	SFM	BFM	SEU	SFM	BFM	SEU
ex5p	292,185	77,344,674	77,929,044	184,214	45,176,056	45,544,484	29.71	25.08	25.11
alu	471,552	152,028,279	152,971,383	328,800	106,137,625	97,166,592	30.27	30.19	30.19
dsip	430,500	121,714,101	122,575,101	276,576	75,420,435	75,973,587	30.91	28.63	28.65
seq	562,131	205,540,815	206,665,077	353,697	122,559,112	123,266,506	29.59	26.29	26.31
des	424,197	96,298,140	97,146,534	245,692	66,632,391	67,123,775	42.08	30.81	30.90
bigkey	485,466	138,266,385	139,237,317	318,670	86,568,229	87,205,569	32.31	29.28	29.30
diffeq	345,561	85,509,339	86,200,461	242,333	62,081,786	62,566,452	29.87	27.40	27.42
frisc	1,227,480	759,018,165	761,473,125	861,195	557,205,584	558,927,974	29.84	26.59	26.60
elliptic	1,286,943	834,739,155	837,313,041	882,495	591,953,893	593,718,883	31.43	29.09	29.09
tseng	209,301	38,648,163	39,066,765	147,774	28,431,596	28,727,144	29.40	26.43	26.47
Average	573,532	250,910,722	252,057,785	393,551	180,654,034	181,441,136	31.54	27.98	28.00

In the following, we first evaluate the total TSV length for the best way of layer placement, which minimize the SEU metrics. Then we evaluate SEU metrics for the best layers placement, which decrease the total TSV length. For the second evaluation, we design a function that compare the entire possible three dimensional FPGA layers placement, and report the minimum total TSV length and its layers placement. In four and six layers 3D FPGAs there are 24 and 720 different layers placement respectively. We tried to make a trade of between total TSV length, and SEU metrics. Since total TSV length, has great effect on propagation delay.

We evaluate the total TSV length and SEU metrics, for any possible three dimensional FPGA layers placement. Then with means of Eq. (7) evaluate the cost for each different placement. At last we report the minimum cost and its placement for each benchmark in table 4.

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TABLE IV: TRADE OF BETWEEN SEU ERROR METRIC AND TOTAL TSV LENGTH

BM	4 LAYERS 3D FPGAS				6 LAYERS 3D FPGAS			
	OPTIMIZED PLACEMENT	TOTAL TSV LENGHT	SEU METRIC	OPTEMIZED COST	OPTIMIZED PLACEMENT	TOTAL TSV LENGHT	SEU METRIC	OPTEMIZED COST
ex5p	1,0,3,2	1505	57,737,426	8.69E+10	1,2,3,4,0,5	3593	47,610,059	1.13E+11
alu4	1,0,3,2	1134	130,298,743	1.48E+11	3,2,1,0,5,4	1928	98,855,329	1.91E+11
dsip	1,0,3,2	197	99,452,097	1.96E+12	3,4,2,1,0,5	423	78,852,914	2.03E+10
seq	1,0,3,2	2213	175,950,794	3.89E+11	1,0,5,4,2,3	3235	138,871,037	3.66E+11
des	1,0,3,2	661	86,406,966	5.73E+10	3,1,2,0,5,4	673	64,215,030	4.32E+11
bigkey	2,1,0,3	527	120,073,429	6.33E+10	1,0,5,2,3,4	608	88,455,065	3.56E+10
diffeq	1,3,0,2	579	63,837,414	4.06E+10	3,1,2,0,5,4	725	54,802,669	3.88E+10
frisc	1,0,3,2	1812	620,500,910	1.12E+12	1,0,5,3,2,4	5362	456,369,526	1.61E+12
elliptic	1,0,3,2	1653	700,419,602	1.15E+12	2,1,3,0,5,4	2901	527,564,021	1.36E+12
tseng	1,0,3,2	217	25,818,755	5.60E+09	1,3,2,0,5,4	1105	24,324,270	1.14E+10

VI. CONCLUSION

In this paper, we proposed a new method for evaluation and mitigation of SEU cost on six layers three-dimensional FPGAs, by means of suitable layers assignment. As the depth of neutron electron holes is restricted, the central layers in 3D FPGAs have lower SEU cost in comparison with other layers. So we shift the most SEU cost layers to the central layers, and decrease the SEU cost, totally. We analysed the effect of this method on 10 MCNC benchmarks. The experimental results show that SEU cost on six layers three-dimensional FPGAs improved about 28%. Then due to the importance of TSV length on delay estimation, we make a trade of between SEU cost, and total TSV length.

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