Fault Diagnosis of Via-Switch Crossbar in Non-volatile FPGA

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***Abstract*—FPGA that exploits via-switches, which are a kind of non-volatile resistive RAMs, for crossbar implementation is attracting attention due to its high integration density and energy efficiency. Via-switch crossbar is responsible for the signal routing by changing on/off-states of via-switches. To verify the via-switch crossbar functionality after manufacturing, fault testing that checks whether we can turn on/off via-switches normally is essential. This paper confirms that a general differential pair comparator successfully discriminates on/off-states of via-switches, and clarifies fault modes of a via-switch by transistor-level SPICE simulation that injects stuck-on/off faults to atom switch and varistor, where a via-switch consists of two atom switches and two varistors. We then propose a fault diagnosis methodology that diagnoses the fault modes of each via-switch using the comparator response difference between normal and faulty via-switches. The proposed method achieves 100% fault detection by checking the comparator responses after turning on/off the via-switch. In case that the number of faulty components in a via-switch is one, the ratio of the fault diagnosis, which exactly identifies the faulty varistor and atom switch inside the faulty via-switch, is 100%, and in case of up to two faults, the fault diagnosis ratio is 79%.**

I. Introduction

Field programmable gate arrays (FPGAs) are gaining their popularity because of the lower development cost than application specific integrated circuits (ASICs). However, conventional FPGAs are still inferior to ASICs regarding operating speed and power consumption [1], [2]. These drawbacks originate from a large number of static random access memory (SRAM)-based programmable switches that are equipped in FPGAs to acquire reconfigurability. To overcome the drawbacks of conventional FPGAs, FPGAs that utilize via-switches, which are a kind of resistive RAMs (RRAMs), as programmable switches instead of SRAM-based ones are drawing attention due to their higher integration density and energy efficiency [3], [4]. In the via-switch FPGA, the crossbar, which has a via-switch at each intersection of horizontal and vertical interconnections, is responsible for the signal routing by changing on/off-states of via-switches. Meanwhile, for ensuring arbitrary routings at FPGA user side, the via-switch FPGA manufacturer needs to verify the via-switch crossbar functionality before the shipment. For this verification, fault testing that checks whether we can turn on/off via-switches normally is essential. However, testing of via-switch FPGA has not been studied so far.

This work is the first one to investigate the fault testing and diagnosis of via-switch crossbar. We confirm that a general differential pair comparator successfully discriminates on/off-states of via-switches, and clarify fault modes of a via-switch using transistor-level SPICE simulation that injects stuck-on/off faults to atom switch and varistor, where a via-switch consists of two atom switches and two varistors. We then propose a fault diagnosis methodology for via-switches in the crossbar that diagnoses the fault modes according to the comparator response difference between normal and faulty via-switches. The proposed method achieves 100% fault detection by checking the comparator responses after turning on/off the via-switch. In case that the number of faulty components in a via-switch is up to two, the successful ratio of the fault diagnosis, which exactly identifies the faulty varistor and atom switch inside the faulty via-switch, is 79%. The fault diagnosis ratio reaches 100% in case that there is up to one faulty component in a via-switch.

II. Via-Switch FPGA

The via-switch is a non-volatile, rewritable, and compact switch, and it is composed of atom switches and varistors [3], [4]. The atom switch consists of a solid electrolyte sandwiched between copper (Cu) and ruthenium (Ru) electrodes. By applying a positive voltage to the Cu electrode, a Cu bridge is formed in the solid electrolyte, and the switch turns on and becomes low resistance state. On the other hand, when a negative voltage is applied, Cu atoms in the bridge are reverted to the Cu electrode, and then the switch turns off and becomes high resistance state. For improving the device reliability, the complementary atom switch (CAS) that consists of two atom switches connected in series with opposite direction is devised. In programming a CAS, a pair of signal line and control lines supply a programming voltage to each atom switch, where a signal line is connected to both ends of a CAS and a control line is connected between two atom switches. During normal operation, on the other hand, only signal lines are used for routing. To accurately provide the programming voltage only to the target atom switch in a switch array, the varistor is connected to the control terminal of CAS. When a programming voltage higher than the threshold value is applied between a signal line and a control line, the varistor supplies programming current to an atom switch. On the other hand, the varistor isolates the control lines from the signal lines during normal operation.

The structure of via-switch FPGA is an array of configurable logic blocks (CLBs), and each CLB is composed of a logic block and a crossbar where a via-switch is placed at each intersection of signal lines [3]. The via-switch in the crossbar is responsible for connection and disconnection between the horizontal and vertical signal lines, and also between the signal lines and logic blocks. Figure 1 illustrates the via-switch based crossbar structure and switch programming steps. Both signal and control lines are aligned horizontally and vertically. Figure 1 exemplifies programming steps in 2x2 crossbar where an atom switch is turned on at each step. A pair of the perpendicular signal and control lines crossing at the

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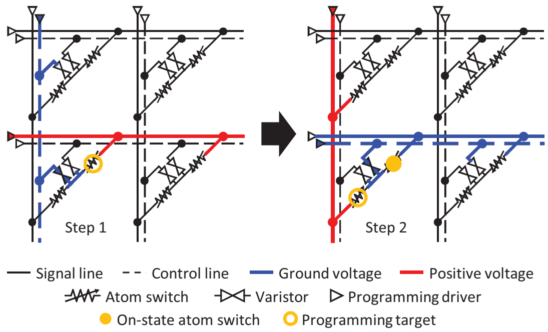

Fig. 1. Via-switch based crossbar structure and switch programming steps.

TABLE I
COMPARATOR OUTPUT IN READ OPERATION OF ATOM SWITCH.

Reference voltage [V]		0.50	0.52	0.54	0.56	0.58	0.60
Comparator output	Atom switch is on	0	0	0	0	0	1
	Atom switch is off	0	0	1	1	1	1

via-switch of interest are used for switch programming. Two programming drivers are activated at each step, and a positive voltage is given to one of the signal lines, and a ground voltage is given to one of the control lines. Other lines are floated. We can see that the via-switch at the bottom left is successfully turned on at steps 1 and 2.

III. Fault Mode Analysis of Via-Switch

To verify the via-switch crossbar functionality after manufacturing, fault testing that checks whether via-switches can be securely turned on and off is indispensable. Aiming at developing a fault testing method, this section analyzes fault modes of a via-switch.

A. Discriminating Via-Switch On/Off-States with Comparator

To discriminate via-switch on/off-states in the crossbar, we add a differential pair comparator that connects to every programming driver through a transistor switch as illustrated in Figure 2. Here, we can share the comparator and programming driver in all the crossbars, and hence the peripheral circuit for programming and testing is negligibly small.

We apply a voltage to the target atom switch in the same manner as programming operation and turn on only the transistor switch that connects the comparator with the driver outputting a ground voltage as depicted in Figure 2. In this read operation, the comparator observes the voltage drop in the target atom switch and compares it with a given reference voltage. Here, the applied voltage in the read operation is lower than the programming voltage, and therefore we never change the on/off-states of the target switch. Table I summarizes the comparator output simulated by transistor-level SPICE simulation. We can see that the comparator output changes from 0 to 1 according to an increase in the reference voltage, and the reference voltage at the boundary between 0 and 1 differs depending on the on/off-states of the target switch. By exploiting this boundary difference, we can discriminate the on/off-states. For example, the atom switch state can be distinguished by choosing 0.56 V as the reference voltage.

The above read method applies a read voltage to a pair of an atom switch and a varistor, and therefore we call this operation as atom switch-varistor read (ASV-read) operation. In addition, we introduce two read operations, namely complementary

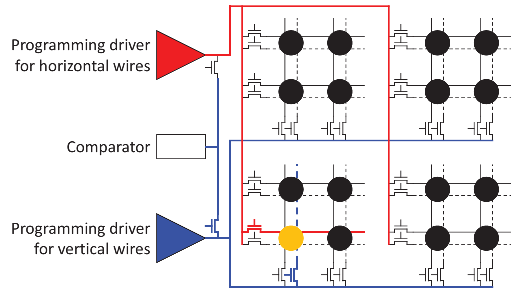

Fig. 2. Connection between comparator, programming drivers, and crossbars.

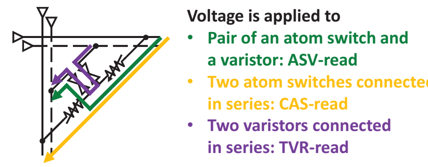

Fig. 3. Path to apply read voltage in ASV-, CAS-, and TVR-read.

atom switch read (CAS-read) and two varistors read (TVR-read). CAS-read applies a voltage to the CAS by activating a pair of drivers that drive the perpendicular two signal lines crossing at the target intersection. One the other hand, TVR-read uses perpendicular two control lines to apply a voltage to two varistors connected in series in a via-switch. The applied voltage in CAS-read is lower than the programming voltage, whereas TVR-read applies a voltage of the same level as the programming voltage to check the varistors state correctly. Figure 3 illustrates each path to apply a voltage in ASV-read, CAS-read, and TVR-read. Here, we do not use the signal path using parallel signal/control lines at the target intersection, where the signal also passes through an atom switch and a varistor, due to the sneak path problem [5].

The SPICE simulation confirms that the comparator response in CAS-read is similar to ASV-read except for the absolute value of the boundary reference voltage. Here, the comparator response for a CAS containing one on-state atom switch and one off-state atom switch is the same as the response to off-state CAS. Meanwhile, the boundary in TVR-read does not change regardless of on/off-states of atom switches since there is no atom switch in the signal path. Table II summarizes the boundary in three read schemes.

B. Via-Switch Fault Modes

This subsection discusses how the comparator response varies when a via-switch includes faulty atom switch or varistor. We inject stuck-on/off faults to atom switch and varistor, and evaluate the boundary reference voltage by SPICE simulation. Here, stuck-on/off faults mean that the two terminals of atom switch or varistor are shorted/opened.

First, we study the case that the atom switch is stuck-on/off. When an atom switch is stuck-on, the boundary reference voltage is unchanged from the non-faulty on-state case even after we apply a programming voltage to turn off the atom switch. Then, we can know there is a fault. The same discussion holds for the stuck-off case.

Next, we discuss the case that the varistor is stuck-on/off. Table III summarizes the boundary reference voltage in ASV-read and CAS-read with faulty varistor. Focusing on ASV-read with stuck-on varistor in Table III, we can see the boundary for on-state switch changes from that of normal case, specifically

TABLE II
BOUNDARY REFERENCE VOLTAGE IN ASV-, CAS-, AND TVR-READ.

Read type	Target switch state	
	On-state	Off-state
ASV-read	0.58 V	0.53 V
CAS-read	0.70 V	0.53 V
TVR-read	0.58 V	0.58 V

TABLE III
BOUNDARY REFERENCE VOLTAGE IN ASV- AND CAS-READ WITH FAULTY VARISTOR.

Read type	Target switch state	Varistor fault type	
		Stuck-on	Stuck-off
ASV-read	On-state	0.77 V	0.53 V
	Off-state	0.53 V	0.53 V
CAS-read	On-state	0.70 V	0.70 V
	Off-state	0.53 V	0.53 V

from 0.58 V in Table II to 0.77 V in Table III. Therefore, we can know there is a fault. On the other hand, when we read off-state atom switch, the boundary is the same for normal and stuck-on cases. In ASV-read with stuck-off varistor, the boundary is fixed to 0.53 V, which is the boundary in normal case with off-state switch, regardless of on/off-states of the target switch. The row of CAS-read in Table III indicates that the boundary for faulty varistor does not change from the normal case. The CAS-read operation applies a read voltage only to the CAS, and hence stuck-on/off faults of the varistor do not affect the comparator response. Table IV shows the boundary of TVR-read in normal and faulty cases. When either varistor in a via-switch is stuck-off, the boundary voltage drops from the normal boundary. On the other hand, when both varistors are not stuck-off and either varistor is stuck-on, the boundary voltage rises compared to the normal case.

We utilize these differences in the boundary reference voltage between normal and faulty cases for the fault diagnosis method proposed in the next section. It should be noted that the comparator response for a via-switch with multiple faulty components is a combination of the above fault modes.

IV. PROPOSED FAULT DIAGNOSIS METHOD

This section proposes a fault diagnosis method that identifies faulty components in a via-switch on the crossbar. First, the following clarifies supposed prerequisites.

- Even when a varistor is stuck-on, we can program the corresponding atom switch normally. This can be achieved by a current-limiting circuit that restricts the programming current appropriately.
- When a varistor is stuck-off, we cannot program the corresponding atom switch since the programming current cannot be provided to the target atom switch.
- Initial state of non-faulty atom switch is off-state, which is a feature of via-switch.
- There is no fault in the comparator, programming drivers, and interconnect wires.

The proposed method enumerates all the combinations of stuck-on/off faults of two atom switches and two varistors in a via-switch. Then, we make a look-up table beforehand that summarizes the boundary reference voltage of ASV-read, CAS-read, and TVR-read after turning on/off the target switch for each fault combination. When we actually diagnose faults, we investigate the boundary of three read operations after programming the target switch, perform a pattern matching with the look-up table, and identify the faults.

TABLE IV
BOUNDARY REFERENCE VOLTAGE IN TVR-READ WITH NORMAL AND FAULTY VARISTORS.

Varistors state	Boundary reference voltage
No fault	0.58 V
If either varistor is stuck-off	0.53 V
Else if either varistor is stuck-on	0.72 V

Table V enumerates all the patterns of comparator response when the number of faulty components in a via-switch is up to two. A via-switch has four components and each component can be stuck-on/off. Supposing the number of faulty components is n, the number of combinations of fault components is given by ${}_4\mathrm{C}_n \times 2^n$. Therefore, the number of combinations in case of up to n faulty components can be calculated by $\sum_{k=0}^{n} {}_4\mathrm{C}_k \times 2^k$. When n is 2, there are 33 combinations.

The proposed method performs ASV-read for both cases after turning on and off the target atom switch. For a CAS, there are four combinations to turn on and off both upper and lower atom switches, and hence we evaluate the boundary reference voltage in all four cases with CAS-read. The proposed method also uses TVR-read. These operations are denoted as abbreviations in Table V. This table also represents the state of the boundary reference voltage with six characters. The explanation of these abbreviations and characters can be found at the bottom of the table. After obtaining the pattern of these six characters with ASV-read of upper and lower atom switches, CAS-read, and TVR-read, we diagnose faulty components in a via-switch.

Following paragraphs discuss fault detectability and diagnosability. First, we evaluate fault detectability. In the ASV-read of an upper atom switch, we use the upper atom switch and the lower varistor. We can see that ID #1-9 in Table V cover all combinations of non-faulty and stuck-on/off upper atom switch and lower varistor. In this case, the response of the upper ASV-read becomes (N, N) only when both upper atom switch and lower varistor have no fault. The response of the remaining eight cases is different from (N, N). By utilizing this difference, we can detect whether a pair of upper atom switch and lower varistor are faulty. The same discussion holds in the ASV-read of lower atom switch with upper varistor. Therefore, we can achieve 100% fault detection of a via-switch by using ASV-read for both upper and lower atom switches.

On the other hand, in terms of fault diagnosability, we cannot identify the faulty components in a via-switch uniquely only with the ASV-read. The column of U-ASV in Table V indicates that ID #3 and 6-9 have the same response of (L, M), and hence we cannot distinguish these patterns. This is mainly because the boundary reference voltage of ASV-read for stuck-off varistor is fixed to that in normal case explained in Section III. For improving fault diagnosability, the proposed method combines the responses of ASV-read, CAS-read, and TVR-read. The column of Diag. shows that fault diagnosability using these three read methods in cases that there are up to one and up to two fault components in a via-switch. When the comparator response is unique in the table, the corresponding fault is diagnosable. We can see that the proposed method can identify the fault component perfectly when there is up to one fault component in a via-switch. When there are up to two faulty components, the diagnosability ratio is $26/33 \times 100 = 79\%$. On the other hand, when only AVS-read is used, this ratio decreases to 33%. CAS-read and TVR-

TABLE V

COMPARATOR RESPONSE DIFFERENCE AND DIAGNOSABILITY IN CASE OF UP TO TWO FAULTY COMPONENTS IN A VIA-SWITCH.

ID	Fault states of via-switch components												Read operation results									Diag.	
	Upper VR			Lower AS			Lower VR			Upper AS			U-ASV		L-ASV		CAS				TVR	1F	2F
	NF	SN	SF	NF	SN	SF	NF	SN	SF	NF	SN	SF	US	UR	LS	LR	SS	SR	RS	RR			
1	✓			✓			✓			✓			N	N	N	N	N	N	N	N	N	Yes	Yes
2	✓			✓			✓				✓		M	H	N	N	M	M	H	M	N	Yes	Yes
3	✓			✓			✓					✓	L	M	N	N	L	M	M	M	N	Yes	Yes
4	✓			✓				✓		✓			R	M	N	N	N	N	N	N	R	Yes	Yes
5	✓			✓				✓			✓		R	R	N	N	M	M	H	M	R	—	Yes
6	✓			✓				✓				✓	L	M	N	N	L	M	M	M	R	—	Yes
7	✓			✓					✓	✓			L	M	N	N	L	M	M	M	D	Yes	No[1]
8	✓			✓					✓		✓		L	M	N	N	M	M	H	M	D	—	Yes
9	✓			✓					✓			✓	L	M	N	N	L	M	M	M	D	—	No[1]
10	✓				✓		✓			✓			N	N	M	H	M	H	M	M	N	Yes	Yes
11	✓				✓		✓				✓		M	H	M	H	M	H	H	H	N	—	Yes
12	✓				✓		✓					✓	L	M	M	H	L	M	M	M	N	—	Yes
13	✓				✓			✓		✓			R	M	M	H	M	H	M	M	R	—	Yes
14	✓				✓				✓	✓			L	M	M	H	L	M	M	M	D	—	Yes
15	✓					✓	✓			✓			N	N	L	M	L	M	M	M	N	Yes	Yes
16	✓					✓	✓				✓		M	H	L	M	L	M	M	M	N	—	Yes
17	✓					✓	✓					✓	L	M	L	M	L	M	M	M	N	—	Yes
18	✓					✓		✓		✓			R	M	L	M	L	M	M	M	R	—	Yes
19	✓					✓			✓	✓			L	M	L	M	L	M	M	M	D	—	No[2]
20		✓		✓			✓			✓			N	N	R	M	N	N	N	N	R	Yes	Yes
21		✓		✓			✓				✓		M	H	R	M	M	M	H	M	R	—	Yes
22		✓		✓			✓					✓	L	M	R	M	L	M	M	M	R	—	Yes
23		✓		✓				✓		✓			R	M	R	M	N	N	N	N	R	—	Yes
24		✓		✓					✓	✓			L	M	R	M	L	M	M	M	D	—	Yes
25		✓			✓		✓			✓			N	N	R	R	M	H	M	M	R	—	Yes
26		✓				✓	✓			✓			N	N	L	M	L	M	M	M	R	—	Yes
27			✓	✓			✓			✓			N	N	L	M	L	M	M	M	D	Yes	No[3]
28			✓	✓			✓				✓		M	H	L	M	L	M	M	M	D	—	Yes
29			✓	✓			✓					✓	L	M	L	M	L	M	M	M	D	—	No[2]
30			✓	✓				✓		✓			R	M	L	M	L	M	M	M	D	—	Yes
31			✓	✓					✓	✓			L	M	L	M	L	M	M	M	D	—	No[2]
32			✓		✓		✓			✓			N	N	L	M	M	H	M	M	D	—	Yes
33			✓			✓	✓			✓			N	N	L	M	L	M	M	M	D	—	No[3]

VR: varistor, AS: atom switch, NF: no fault, SN/SF: stuck-on/off
U-ASV/L-ASV: ASV-read of upper/lower atom switch, US/UR/LS/LR: read after turning on/off/on/off upper/upper/lower/lower atom switch
SS/SR/RS/RR: read after turning on/on/off/off upper atom switch and turning on/off/on/off lower atom switch
N: normal response, M: fault is masked, H/L: boundary is the same as on-state/off-state switch, R/D: boundary rises/drops
Diag.: diagnosability, 1F/2F: up to one/two faulty components in a via-switch
Rows that have the same superscript number of "No" in diagnosability column share the same comparator response.

read help elevate the fault diagnosability by 46%.

V. DISCUSSION

A relation between a fault rate of via-switch components and a percentage of faulty via-switches in an practically-sized 100x100 crossbar is shown in Figure 4. This evaluation randomly injects faults assuming that four components in a via-switch have the same fault rate, and plots the average value of 10,000 trials. This figure also categorizes faulty via-switches according to the number of faulty components. We can see that via-switches with a single faulty component are dominant, especially when the fault rate is low. When the fault rate of each component is 0.1, the percentage of faulty via-switches is more than 30%. Therefore, in the crossbar with a practical percentage of faulty via-switches, it is important to identify the faulty component in via-switches with only one faulty component. From this point of view, the proposed method is suitable. For example, when we suppose that there is up to one fault in a via-switch, the percentage of diagnosable via-switches reaches 99% when the fault rate is 0.05.

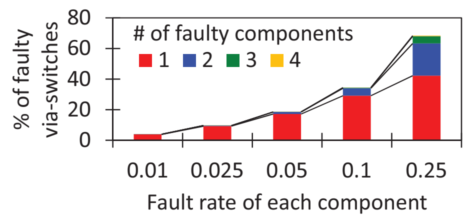

Fig. 4. Percentage of faulty via-switches in 100x100 crossbar when via-switch fault rate varies.

VI. CONCLUSION

This paper confirmed that a general comparator could discriminate on/off-states of via-switches in the crossbar-based FPGA and clarified fault modes of a via-switch by SPICE simulation. We have proposed a fault diagnosis method that identifies faulty via-switch components according to the comparator response difference between normal and faulty cases. The proposed method achieves 100% fault detection. The successful ratios of the fault diagnosis are 100% and 79% in cases that the number of faulty components in a via-switch is up to one and up to two, respectively.

ACKNOWLEDGMENT

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