

March Tests for Realistic Faults in Two-Port Memories

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Abstract

This paper starts with an overview of realistic faults models for two-port memories, divided into single-port faults and unique two-port faults. The latter faults can not be detected with the conventional single-port memory tests; they require special tests. Thereafter, the paper presents a set of four march tests detecting the unique two-port faults. Three of the tests have a time complexity of $\theta(n)$ and one of $\theta(\sqrt{n})$, whereby n is the size of the two-port memory cell array. Two of the four tests have been implemented at Intel and applied to 1500 two-port memories passing all single-port tests. The test results show that two dies fail to pass the implemented tests, which means that the tests are superior.

1 Introduction

In spite of growing use of *Multi-port (MP)* memories, limited work has been published. In [1], an *ad hoc* test with no specific fault model was described. In [2], a BIST circuit, based on a serial interfacing technique for embedded *two-port (2P)* memories, was reported. However, the used fault models were very simplistic and restricted to a *subset* of shorts between ports. For the same fault models, modified march tests and BIST circuits were reported in [3,4,5]. In [6, 7] a *complex coupling* fault model, based on two or more *weak idempotent coupling fault* activated simultaneously, was developed. In [8, 9, 10], a complete theoretical framework for *weak faults* in 2P memories was made and a complete set of fault models (based on weak faults), together with their tests, was established. In [11], port interferences in 2P memories were experimentally analyzed, based on an industrial design and SPICE simulation; however, the analysis was restricted to only the interference between the two ports.

It can be seen from the above that little *experimental* research has been done on testing MP memories. In this paper realistic fault models for 2P memories will be presented based on [12], together with optimal tests that guarantee a high fault coverage

This paper is organized as follows: Section 2 gives an

overview of realistic fault models for a 2P memory cell array as established by [12]; Section 3 establishes march tests for the 2PFs; Section 4 gives some tests results; while Section 5 ends with conclusions.

2 Fault models for 2P-SRAM

Many faults in a memory circuit are caused by undesired particles called *spot defects (SDs)*. Depending on the conductivity of the SDs, they can cause undesired connections or disconnections in the memory. They can be divided into three groups: opens, shorts, and bridges. An *Open* is an extra resistance within a connection; a *short* is an undesired resistive path between a node and V_{cc} or V_{ss} ; while a *bridge* is an undesired resistive path between two connections, which are not V_{cc} or V_{ss} .

In [12], a complete experimental analysis for opens, shorts, and bridges in a differential 2P memory cell (with two *read-write* ports) has been given. SPICE simulation of all possible SDs has been performed, by examining the resistance range of each SD from 0 to ∞ , and by verifying all allowed operations in the analyzed 2P memory; i.e., all SP operations (read and write), and all 2P operations (simultaneous read of a same/different location(s), simultaneous writing of different locations, simultaneous read and write of a same/different location(s)). During the simulation, any faulty behavior (in the presence of certain SD) is reported in terms of a *fault primitive (FP)*. A FP is a compact notation describing the fault. The simulation results show that the sensitized FPs are *strongly dependent* on the resistance value of the defect. These FPs are thereafter translated into *functional fault models (FFMs)*, used to design tests. A FFM is defined as a non empty set of FPs. This section derives FFMs from the FPs, as established by [12]. The FFMs for 2P memories are divided into single-port FFMs and two-port FFMs.

2.1 Single-port FFMs

Single-port FFMs (abbreviated as *IPFs*) are divided into faults involving a *single-cell (IPF1s)* and faults involving

two-cell (1PF2s). The 1PF1s consist of single-cell FPs and have the property that the cell used for sensitizing the fault is the same cell as where the fault appears; while the 1PF2s consist of two-cell FPs and have the property that the application of an SP operation to a cell c_a (or the state of the cell c_a) has as a consequence that a fault will be sensitized in another cell c_v . Before listing the realistic 1PFs, the to be used notation will be introduced:

- $\langle S/F/R \rangle$ (or $\langle S/F/R \rangle_v$): denotes a FP involving a single-cell; the cell c_v (victim cell) used to sensitize a fault is the same as where the fault appears. S describes the value/operation sensitizing the fault; $S \in \{0, 1, w0, w1, w \uparrow, w \downarrow, r0, r1, \forall\}$, whereby 0 (1) denotes a zero (one) value, $w0$ ($w1$) denotes a write 0 (1) operation, $w \uparrow$ ($w \downarrow$) denotes an up (down) transition write operation, $r0$ ($r1$) denotes a read 0 (1) operation, and \forall denotes any operation ($\forall \in \{0, 1, w1, w0, w \uparrow, w \downarrow, r1, r0\}$); if the fault effect of S appears after a time T , then the sensitizing operation is given as S_T .

- $\langle S_a; S_v/F/R \rangle$ (or $\langle S_a; S_v/F/R \rangle_{a,v}$): denotes a FP involving two cells; S_a describes the sensitizing operation or state of the aggressor cell (a-cell); while S_v describes the sensitizing operation or state of the victim cell (v-cell). The a-cell (c_a) is the cell sensitizing a fault in another cell called the v-cell (c_v). The set of S_i is defined as: $S_i \in \{0, 1, X, w0, w1, r0, r1\}$ ($i \in \{a, v\}$), whereby $X \in \{0, 1\}$ is the don't care value.

In both notations, F describes the value of the faulty cell (v-cell); $F \in \{0, 1, \uparrow, \downarrow\}$, whereby \uparrow (\downarrow) denotes an up (down) transition. R describes the logical value which appears at the output of the memory if the sensitizing operation applied to the v-cell is a read operation: $R \in \{0, 1, ?, -\}$, whereby ? denotes an undefined or random logical value which can occur if the voltage difference between the bit lines (used by the sense amplifier) is very small. A '-' in R means that the output data is not applicable in that case; e.g., if $S = w0$, then no data will appear at the memory output, and therefore R is replaced by a '-'.

2.1.1 The 1PF1 fault subclass

In [12], and based on the fault behaviors found by simulating all SDs, the following 1PF1s have been derived:

Stuck-at Fault (SAF): the logic value of a cell is always '0' or always '1'. The SAF consists of two FPs: $\langle \forall/0/- \rangle$, and $\langle \forall/1/- \rangle$.

Transition Fault (TF): the cell fails to undergo a transition ($0 \rightarrow 1$ or $1 \rightarrow 0$) when it is written. The TF consists of two FPs: $\langle w \uparrow/0/- \rangle$ and $\langle w \downarrow/1/- \rangle$.

No Access Fault (NAF): The state of the accessed cell can not be changed with write operations, and read operations return random or an undefined values. The NAF consists of the following FPs which occur simultaneously: $\langle w \uparrow/0/- \rangle$,

$\langle w \downarrow/1/- \rangle$, $\langle r0/0/? \rangle$ and $\langle r1/1/? \rangle$.

Data Retention Fault (DRF): the cell fails to retain its logic value after some period of time T . The DRF consists of four FPs: $\langle 1_T/ \downarrow/- \rangle$, $\langle 0_T/ \uparrow/- \rangle$, $\langle 1_T/?/- \rangle$, and $\langle 0_T/?/- \rangle$.

Read Destructive Fault (RDF): a rx operation performed to the cell changes the data in the cell into \bar{x} and it returns the logic value \bar{x} . The RDF consists of two FPs: $\langle r0/ \uparrow/1 \rangle$ and $\langle r1/ \downarrow/0 \rangle$.

Deceptive Read Destructive Fault (DRDF): a rx operation performed to the cell changes the data in the cell into \bar{x} while it returns the logic value x . The DRDF consists of two FPs: $\langle r0/ \uparrow/0 \rangle$ and $\langle r1/ \downarrow/1 \rangle$.

Incorrect Read Fault (IRF): a rx operation performed to a cell returns the logic value \bar{x} , while the state of the cell is not changed. The IRF consists of two FPs: $\langle r0/0/1 \rangle$ and $\langle r1/1/0 \rangle$.

Random Read Fault (RRF): a rx operation performed to a cell returns a random value, while the state of the cell is not changed. The RRF consists of two FPs: $\langle r0/0/? \rangle$ and $\langle r1/1/? \rangle$.

Undefined State Fault (USF): a read or a write operation performed to a cell brings the cell into an undefined state; the read operation then returns a random value. The USF consists of four FPs: $\langle w0/?/- \rangle$, $\langle w1/?/- \rangle$, $\langle r0/?/? \rangle$ and $\langle r1/?/? \rangle$.

2.1.2 The 1PF2 fault subclass

The 1PF2 fault subclass consists of coupling faults. In [12], the following FPMs for 1PF2s have been derived:

Disturb Coupling Fault (CF_{ds}): The v-cell undergoes a transition due to a $w0$ or a $w1$ operation applied to the a-cell. The CF_{ds} consists of four FPs: $\langle w0;0/ \uparrow/- \rangle$, $\langle w0;1/ \downarrow/- \rangle$, $\langle w1;0/ \uparrow/- \rangle$ and $\langle w1;1/ \downarrow/- \rangle$.

State Coupling Fault (CF_{st}): The v-cell is forced to a certain logic value (0 or 1), only if the a-cell is in a given state (0 or 1). The CF_{st} consists of four FPs: $\langle 1; X/0/- \rangle$, $\langle 1; X/1/- \rangle$, $\langle 0; X/0/- \rangle$, and $\langle 0; X/1/- \rangle$.

Incorrect Read Coupling Fault (CF_{ir}): A read operation applied to the v-cell returns an incorrect value if the a-cell is in a given state; the state of the v-cell is not changed. The CF_{ir} consists of four FPs: $\langle 0; r0/0/1 \rangle$, $\langle 0; r1/1/0 \rangle$, $\langle 1; r0/0/1 \rangle$, and $\langle 1; r1/1/0 \rangle$.

Random Read Coupling Fault (CF_{rr}): A read operation applied to the v-cell returns a random value if the a-cell is in a given state; the state of the v-cell is not changed. The CF_{rr} consists of four FPs: $\langle 0; r0/0/? \rangle$, $\langle 0; r1/1/? \rangle$, $\langle 1; r0/0/? \rangle$, and $\langle 1; r1/1/? \rangle$.

Read Destructive Coupling Fault (CF_{rd}): A read operation applied to the v-cell causes a transition in the v-cell and returns an incorrect value, if the a-cell is in a given state. The CF_{rd} consists of four FPs: $\langle 0; r0/ \uparrow/1 \rangle$, $\langle 0; r1/ \downarrow/0 \rangle$, $\langle 1; r0/ \uparrow/1 \rangle$, and $\langle 1; r1/ \downarrow/0 \rangle$.

2.2 Two-port FFMs

In the representation of the 2PFs, the following terminology will be introduced [12]:

- **Strong fault:** This is a memory fault that can be **fully sensitized** by an SP operation; i.e., a SP write or a read operation fails. That means that the state of the cell is incorrectly changed, can not be changed, or that the sense amplifier returns an incorrect result.

- **Weak fault:** This is a fault which is **partially** sensitized by an SP operation; e.g., a defect that creates a small disturbance of the voltage of the true node of the cell. However, a fault can be *fully sensitized* when two (or more) weak faults are simultaneously sensitized since their fault effects can be additive. This can occur when a 2P operation is applied.

Two-port FFMs (2PFs) are faults that can not be sensitized using SP operations; they require the use of the two ports simultaneously. They can be considered as a combination of *two weak faults* [12], and divided into faults *involving a single cell (2PF1s)* and faults *involving two cells (2PF2s)*; see Figure 1. The 2PF1s are based on a combination of *two weak single-cell faults*. In addition, the two a-cells are the same as the v-cell. In order to sensitize a 2PF1, the same cell has to be acted upon simultaneously via the two ports.

The 2PF2s are based on a combination of weak single-cell faults and weak faults involving two cells. Depending on to which cells the two simultaneous operations are applied (to the a-cell and/or to the v-cell), the 2PF2s are divided into three types [12] (see Figure 1):

1. **The 2PF2_{av}:** In this case, the 2PF is a combination of a weak single-cell fault and a weak fault involving two cells. Note that the weak single-cell fault is present in the v-cell of the weak fault involving two cells.

2. **The 2PF2_{aa}:** In this case, the 2PF is a combination of two weak faults involving two cells; both weak faults have the same a-cell as well as the same v-cell; see Figure 1.

3. **The 2PF2_{vv}:** In this case, the 2PF is a combination of two weak faults: one weak fault involving two cells, and one weak single-cell fault. The weak fault involving two cells requires that the operation has to be performed to the v-cell (solid arrow in the figure), while the a-cell has to be in certain state (dashed arrow in the figure).

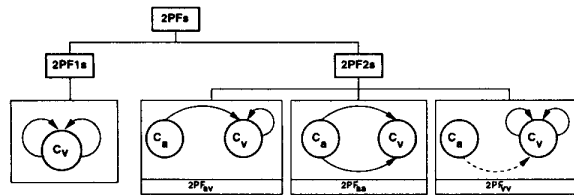


Figure 1. Classification of 2PFs

Before listing the FPs for 2PFs, the to be used notation will be introduced. To denote a 2PF1 fault, the following nota-

tion for FPs will be used:

- $\langle S_1 : S_2/F/R \rangle_v$ denotes a two-port FP involving a single cell (v-cell). This FP requires the use of the two ports *simultaneously*. S_1 and S_2 describe the sensitizing operations or states of the cell; ":" denotes the fact that S_1 and S_2 are applied *simultaneously* through the two ports. F describes the behavior or the state of the v-cell. Note that the sensitizing operations are applied to the same cell as where the fault appears. R is the read result of S_1 (and/of S_2) if it is a read operation.

To denote 2PF2s, three notations can be identified, depending on the type of the 2PF2; i.e., depending on the cell(s) to which the two simultaneous sensitizing operations are applied; either to the aggressor cell and/or to the victim cell.

- $\langle S_a : S_v/F/R \rangle_{a,v}$ denotes a FP whereby one sensitizing operation, S_a , is applied to the a-cell, and the other sensitizing operation, S_v , is applied to the v-cell.

- $\langle S_a : S_a; S_v/F/R \rangle_{a,v}$ denotes a FP whereby both sensitizing operations, S_a , are applied to the a-cell. S_v denotes the state of the v-cell.

- $\langle S_a; S_v : S_v/F/R \rangle_{a,v}$ denotes a FP whereby both sensitizing operations, S_v , are applied to the v-cell. S_a describes the state of the a-cell.

Note that F and R in the above notations are the same as with the notation for 2PF1 FPs. In addition to the notation for FPs, the following will be used for describing 2PFs:

- $\langle fault_1 \rangle \& \langle fault_2 \rangle$ denotes a 2PF consisting of two weak faults; '&' denotes the fact that the two faults *in parallel* (i.e., simultaneously) form the 2PF.

- F denotes a *strong fault* F, while wF denotes the *weak fault* F. For example, RDF denotes a strong Read Disturb Fault, while $wRDF$ denotes a weak Read Disturb Fault.

2.2.1 FFMs for the 2PF1 fault subclass

The 2PF1 subclass consists of three FFMs:

$wDRDF \& wDRDF$: Applying simultaneous read operations to a single cell causes the cell to flip; while the sense amplifiers return *the correct* values. The $wDRDF \& wDRDF$ consists of two FPs:

$\langle r0 : r0/\uparrow/0 \rangle_v$, and $\langle r1 : r1/\downarrow/1 \rangle_v$.

$wRDF \& wRDF$: Applying simultaneous read operations to a single cell causes the cell to flip, and the sense amplifiers return *incorrect* values. The $wRDF \& wRDF$ consists of two FPs:

$\langle r0 : r0/\uparrow/1 \rangle_v$ and $\langle r1 : r1/\downarrow/1 \rangle_v$.

$wRDF \& wTF$: A cell fails to undergo a write transition if a read operation is applied to the same cell simultaneously. The $wRDF \& wTF$ consists of two FPs:

$\langle r0 : w/\uparrow/0/- \rangle_v$ and $\langle r1 : w/\downarrow/1/- \rangle_v$. Note that a simultaneous read and write to the same location is allowed in the considered memory, the read result is then discarded.

It should be noted that the first two FFM's are caused by partial opens at the drain/source of the pull down transistor of the cell, a short to V_{ss} at the true/false node of the cell, or a bridge between a node of a cell and a word line of an adjacent cell in the same column; while the third FFM is caused by bridges between bit lines (of a same column) belonging to different ports *and* different sides of the cell [12].

2.2.2 FFM's for the 2PF2 fault subclass

The FFM's for the 2PF2 fault subclass are divided into three types: the 2PF2_{av}, the 2PF2_{aa}, and the 2PF2_{vv}.

The 2PF2_{av}: This type can be caused by bridges between bit lines of different ports belonging to the same/different column(s) [12]; it consists of three FFM's.

wCF_{ds}&wRDF: A read operation applied to the v-cell flips the cell and the sense amplifier returns an incorrect value if a write operation is applied to the a-cell *simultaneously*. The *wCF_{ds}&wRDF* consists of the following FPs: $\langle w0 : r0 / \uparrow / 1 \rangle$, $\langle w0 : r1 / \downarrow / 0 \rangle$, $\langle w1 : r0 / \uparrow / 1 \rangle$, and $\langle w1 : r1 / \downarrow / 0 \rangle$.

wCF_{ds}&wIRF: A read operation applied to the v-cell returns an incorrect value if a write operation is applied to the a-cell *simultaneously*. It should be noted that the state of the v-cell does not change. The *wCF_{ds}&wIRF* consists of the following FPs: $\langle w0 : r0 / 0 / 1 \rangle$, $\langle w0 : r1 / 1 / 0 \rangle$, $\langle w1 : r0 / 0 / 1 \rangle$, and $\langle w1 : r1 / 1 / 0 \rangle$.

wCF_{ds}&wRRF: A read operation applied to the v-cell returns a random value if a write operation is applied to the a-cell *simultaneously*. Note that the state of the v-cell does not change. The *wCF_{ds}&wRRF* consists of the following FPs: $\langle w0 : r0 / 0 / ? \rangle$, $\langle w0 : r1 / 1 / ? \rangle$, $\langle w1 : r0 / 0 / ? \rangle$, and $\langle w1 : r1 / 1 / ? \rangle$.

The 2PF2_{aa}: This type consists of only one FFM: *wCF_{ds}&wCF_{ds}*. Applying two simultaneous operations to the a-cell will sensitize a fault in the v-cell; i.e., the v-cell flips. The *wCF_{ds}&wCF_{ds}* consists of following FPs: $\langle w0 : rx / 0 / \uparrow / - \rangle$, $\langle w0 : rx / 1 / \downarrow / - \rangle$, $\langle w1 : rx / 0 / \uparrow / - \rangle$, and $\langle w1 : rx / 1 / \downarrow / - \rangle$; whereby x can be 0 or 1.

The 2PF2_{vv}: This type also consists of only one FFM: *wCF_{rd}&wRDF*. Applying two simultaneous read operations to the v-cell will cause the cell to flip if the a-cell is in a certain state. The read operations then return wrong values. The *wCF_{rd}&wRDF* consists of four FPs: $\langle 0; r0 : r0 / \uparrow / 1 \rangle$, $\langle 0; r1 : r1 / \downarrow / 0 \rangle$, $\langle 1; r0 : r0 / \uparrow / 1 \rangle$, and $\langle 1; r1 : r1 / \downarrow / 0 \rangle$.

It should be noted that the 2PF_{aa} and the 2PF2_{vv} can be caused by bridges between nodes of adjacent cells belonging to the same column, same row, or same diagonal [12].

3 March tests for 2PFs

As mentioned in the previous section, FFM's for 2P memories can be divided into 1PFs and 2PFs. Therefore the test procedure can be divided into two parts: (a) Test(s) to detect 1PFs, and (b) Test(s) to detect 2PFs. For the detection of 1PFs, which consist of the conventional faults occurring in SP memories, a test such as MATS+, March C-, Walking 1/0, etc. [13] can be used. For the detection of 2PFs (which are divided into 2PF1s and 2PF2s), special tests are required.

This section gives march tests for detecting the 2PFs of Section 2. In order to describe such tests, march notation has to be extended such that MP memory tests can be specified.

3.1 Notation for March tests

The extension will be done as follows:

- A complete march test is delimited by the '{...}' bracket pair; while a march element is delimited by the '(...)' bracket pair. The march elements are separated by semicolons, and the operations within a march element are separated by commas. The MATS+ march test $\{\uparrow(w0); \uparrow(r0, w1); \downarrow(r1, w0)\}$ consist of the march elements $\uparrow(w0)$, $\uparrow(r0, w1)$, and $\downarrow(r1, w0)$. Note that all operations of a march element are performed at a certain address, before proceeding to the next address.

- The operations applied in parallel to the ports are separated using colons, and the port numbers to which the parallel operations are applied is determined implicitly; e.g., $(r0 : w1)$ denotes two simultaneous operations: a $r0$ applied to first port (P1), and a $w1$ applied to P2.

- The character 'n' denotes *no* operation, while the character '-' denotes *any* allowed operation. E.g., $(r0 : n)$ denotes a $r0$ operation via P1, and no operation on P2.

- The cell to which the operation is applied can be specified explicitly by subscripting the corresponding operation. E.g., $(r0_{r,c})$ denotes a $r0$ operation applied to a cell with row r and column c .

- $\uparrow_{r=0}^{R-1}$: denotes $\uparrow_{r=0}^{R-1}$ or $\downarrow_0^{r=R-1}$, and $\uparrow_{r_1=0}^{R-1} \uparrow_{r_2=r_1+1}^{R-1}$: denotes a nested addressing sequence, whereby r_1 goes from 0 to $R-1$; and for each value of r_1 , r_2 goes from r_1+1 to $R-1$.

3.2 Test for 2PF1s

The 2PF1s consist of three FFM's: *wDRDF&DRDF*, *wRDF&wRDF*, and *wRDF&wTF* (see Section 2.2.1). In order to sensitize a 2PF1, the same cell has to be acted upon simultaneously via the two ports; see Figure 1. Each FFM consists of two FPs: the *wDRDF&DRDF* consists of $\langle r0 : r0 / \uparrow / 0 \rangle_v$ and $\langle r1 : r1 / \downarrow / 1 \rangle_v$; the *wRDF&wRDF* consists of $\langle r0 : r0 / \uparrow / 1 \rangle_v$ and $\langle r1 : r1 / \downarrow / 0 \rangle_v$; while *wRDF&wTF* consists of $\langle r0 : w \uparrow / 0 / - \rangle_v$ and $\langle r1 : w \downarrow / 1 / - \rangle_v$.

The test, *March r2PF1*, (March test for realistic 2PF1) shown in Figure 2, detects all above 2PF1 faults; it consists of three march elements: M_0 , M_1 , and M_2 . M_0 consists of one operation and initializes the memory cells to 0. The first operation of M_1 (i.e., ' $w1 : r0$ ') sensitizes the FPs $\langle r0 : w \uparrow / 0 / - \rangle_v$, that will be detected by the next operation. The latter will sensitize $\langle r1 : r1 / \downarrow / 1 \rangle_v$, and sensitize and detect $\langle r1 : r1 / \downarrow / 0 \rangle_v$. The third operation of the same march element will detect $\langle r1 : r1 / \downarrow / 1 \rangle_v$. A similar explanation can be given for the three operations of M_2 . Note that the '-' in the third operation of M_1 (M_2) can be replaced with a $r1$ ($r0$) operation. Note also that the test length of the test is $7n$.

It should be noted that simultaneous read and write operations of the same location is assumed to be allowed in the analyzed 2P memory. If this is not supported, then the FFM: *RDF&wTF* is not realistic; as a consequence the test can be simplified.

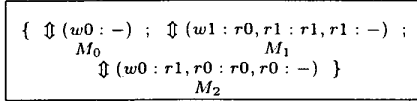


Figure 2. March r2PF1

3.3 Tests for the 2PF2s

The 2PF2s consist of faults involving two cells. Depending on to which cells the simultaneous operations are applied to, three types of 2PF2s have been distinguished (see Section 2.2.2): (a) 2PF2_{av}, (b) 2PF2_{aa}, and (c) 2PF2_{vv}. Below, tests for each type of 2PF2s will be introduced.

Test for 2PF2_{av}: The 2PF2_{av}s consist of three FFMs: *wCF_{ds}&wRDF*, *wCF_{ds}&wIRF*, and *wCF_{ds}&wRRF*; each with four FPs. All these faults are caused by bridges between bit lines belonging to the same or adjacent column(s) and belonging to different ports [12]. In addition, their sensitization requires the application of one operation to the a-cell and one operation to the v-cell simultaneously, whereby the a-cell and the v-cell belong to the same/or adjacent column(s). Since a given bit line is connected to R cells (assume memory cell array with R rows and C columns, and $R = C$ for simplicity), the 2PF2_{av} can influence the operations applied to all these cells. Therefore, one can restrict to apply the test to only two adjacent cells in the same column and two adjacent cells in the same row (i.e., adjacent columns).

The test for the 2PF2_{av} faults is shown in Figure 3, and is referred as *March r2PF2_{av}*. The cell to which a certain operation is applied is specified explicitly by subscripting the corresponding operation; e.g., ($w1_{i,i} : r0_{i+1,i}$) denotes a $w1$ operation applied to a cell with row i and column i via the first port (P1) and a $r0$ operation applied to a cell with row $i + 1$ and column i via P2. In the test,

M_0 initializes the main diagonal and its two neighboring diagonals to 0; M_3 does the same with inverted data. M_1 and M_4 sensitize and detect the 2PF2_{av} faults in adjacent cells in the same column, while M_2 and M_5 do the same but for adjacent cells in the same row. E.g., the operation ' $w1_{i,i} : r0_{i+1,i}$ ' in M_1 sensitizes and detects the faults $\langle w1 : r0 / \uparrow / 1 \rangle_{a,v}$ and $\langle w1 : r0 / 0 / 1 \rangle_{a,v}$, and it may detect $\langle w1 : r0 / 0 / ? \rangle_{a,v}$. March 2PF2_{av} guarantees the detection of *wCF_{ds}&wRDF* and *wCF_{ds}&wIRF*, but it does not guarantee the detection of *wCF_{ds}&wRRF*. This is because the read operation returns a random value. However, applying the test multiple times can detect the fault probabilistically. Note that the test length of the test is $14R$, which means that the time complexity is $\theta(R) = \theta(\sqrt{n})$.

For simplicity, it is assumed here that $R = C$. If this is not the case, then the row indexes (e.g., i) and the column indexes (e.g., j) in the operation; e.g., ' $w1_{i,j} : n$ ' should be replaced with ' $i \bmod^1 R$ ' and ' $j \bmod C$ ' respectively. In addition, the test length of the test will be $14 * \max(R, C)$.

Test for 2PF2_{aa}: The 2PF2_{aa} consists of one FFM (i.e., *wCF_{ds}&wCF_{ds}*) with the following FPs: $\langle w0 : rx ; 0 / \uparrow / - \rangle$, $\langle w0 : rx ; 1 / \downarrow / - \rangle$, $\langle w1 : rx ; 0 / \uparrow / - \rangle$, and $\langle w1 : rx ; 1 / \downarrow / - \rangle$; whereby x can be 0 or 1. The test, *March r2PF2_{aa}*, detecting all 2PF2_{aa} faults, is given in Figure 4. The second and the third operations of M_2 sensitize *wCF_{ds}&wCF_{ds}* faults when the value of the fault effect is 1. If the address order is increasing, then the fault will be detected by the first operation of M_1 when the v-cell has a higher address than the a-cell, and by the first operation of M_3 in the other case. A similar explanation can be given for M_3 and M_4 in the case that the value of the fault effect is 0. Note that the test length is $10n$.

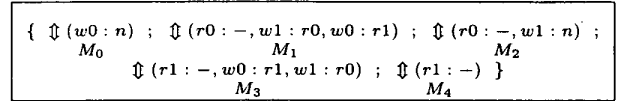


Figure 4. March r2PF2_{aa}

Test for 2PF2_{vv}: The 2PF2_{vv} consists only of one FFM: *CF_{rd}&wRDF* with four FPs: $\langle 0 ; r0 : r0 / \uparrow / 1 \rangle_{a,v}$, $\langle 1 ; r0 : r0 / \uparrow / 1 \rangle_{a,v}$, $\langle 0 ; r1 : r1 / \downarrow / 0 \rangle_{a,v}$, and $\langle 1 ; r1 : r1 / \downarrow / 0 \rangle_{a,v}$. Figure 5 shows *March r2PF2_{vv}* detecting *wCF_{rd}&wRDF* faults. M_0 initializes all memory cells to 0. M_1 sensitizes and detects the faults when the a-cell state is 0: $\langle 0 ; r0 : r0 / \uparrow / 1 \rangle$ is detected by the first operation, while $\langle 0 ; r1 : r1 / \downarrow / 0 \rangle$ is detected by the third operation; the operation ' $w0 : -$ ' is added to M_1 such the contents of the cells will be 0 (after each sequence of operations), which is the required state of the a-cell. M_3 sensitizes and detects the faults when the a-cell's state is 1. Note that the test length of March 2PF2_{vv} is $10n$.

¹ $a \bmod b$ = the remainder of dividing a by b

$$\left\{ \begin{array}{l} \Downarrow_{i=0}^{R-1} (w0_{i,i} : n, w0_{i,i+1} : n, w0_{i+1,i} : n) ; \Downarrow_{i=0}^{R-1} (w1_{i,i} : r0_{i+1,i}, w0_{i,i} : r0_{i+1,i}) ; \Downarrow_{i=0}^{R-1} (w1_{i,i} : r0_{i+1,i}, w0_{i,i} : r0_{i+1,i}) ; \\ M_0 \qquad \qquad \qquad M_1 \qquad \qquad \qquad M_2 \\ \Downarrow_{i=0}^{R-1} (w1_{i,i} : n, w1_{i,i+1} : n, w1_{i+1,i} : n) ; \Downarrow_{i=0}^{R-1} (w0_{i,i} : r1_{i+1,i}, w1_{i,i} : r1_{i+1,i}) ; \Downarrow_{i=0}^{R-1} (w0_{i,i} : r1_{i+1,i}, w1_{i,i} : r1_{i+1,i}) \end{array} \right\}$$

Figure 3. March r2PF2_{av}

$$\left\{ \begin{array}{l} \Downarrow (w0 : -) ; \Downarrow (r0 : r0, w1 : -, r1 : r1, w0 : -) ; \\ M_0 \qquad \qquad \qquad M_1 \\ \Downarrow (w1 : -) ; \Downarrow (r1 : r1, w0 : -, r0 : r0, w1 : -) \end{array} \right\}$$

Figure 5. March r2PF2_{vv}

4 Test results

Inductive Fault Analysis (IFA) has been performed on the layout of the analyzed 2P memory in order to determine the probabilities of occurrence of 1PFs and 2PFs [12]. The results show that 94% of the faults are 1PFs, and 6% are 2PFs, and that 99.92% of the 2PFs are 2PF1 and 2PF2_{av} faults. Therefore, and in order to reduce the test time, one can restrict to the detection of the 2PF1 and 2PF2_{av} faults.

Versions of the two march tests, March r2PF1 and March r2PF2_{av}, detecting such faults have been implemented at Intel. The tests have been applied to 2P memory (good) dies that pass all used SP memory tests. The test results show that from 1500 good dies *two* dies fail to pass the implemented test; i.e., 0.13% of the good dies. That means that these tests catch faults that can not be caught using SP memory tests. Such faults are the 2PFs which require the use of the two ports simultaneously in order to be sensitized.

5 Conclusions

In this paper, realistic fault models for 2P memories have been presented and divided into single-port faults (1PFs) and two-port faults (2PFs). The 1PFs can be detected using the conventional SP memory tests, while the 2PFs require special tests; this is because the sensitization of 2PFs requires the use of the two ports simultaneously. The 2PFs are divided into 2PFs involving a single cell (2PF1s) and 2PFs involving two-cells (2PF2s). Depending on to which cells the two simultaneous operations are applied (i.e., to the a-cell and/or to the v-cell), the 2PFs are divided into 2PF2_{av}s (whereby one sensitizing operation has to be applied to the a-cell and one to the v-cell), 2PF2_{aa}s (whereby both sensitizing operations have to be applied to the a-cell), and 2PF2_{vv}s (whereby both sensitizing operations have to be applied to the v-cell). Four march tests to detect such faults have been introduced: March r2PF1 to detect 2PF1 faults, March r2PF2_{av} to detect 2PF2_{av} faults, March r2PF2_{aa} to detect 2PF2_{aa} faults, and March r2PF2_{vv} to detect 2PF2_{vv} faults. These tests have test lengths of $7n$, $14 \cdot \max(R, C)$, $10n$, and $10n$ respectively; whereby n is the size of the 2P memory cell array with R rows and C columns.

In addition, Inductive Fault Analysis has been applied to the layout of the analyzed 2P memory in order to determine the probability of occurrence of 1PFs as well as 2PFs. The results show that 94% of the faults are 1PFs, while 6% of the faults are 2PFs. Moreover, the 1PFs and the 2PF2_{av}s consist of 99.92% of the 2PFs. Therefore, only (two) march tests, detecting the 1PF1s and the 2PF2_{av}s, have been implemented at Intel in order to reduce the test time, while the fault coverage remains high. The two tests have been applied to 1500 (good) dies passing all used SP tests. The results show that *two* dies fail to pass the implemented tests; i.e. 0.13% of the good dies. Considering the drive toward shipping products with a zero defect level, this 0.13% is an important improvement!

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