A Fault Primitive Based Analysis of Dynamic Memory Faults

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Abstract— **The new memory technologies and processes are introducing defects that cause faults that were unknown previously. One of the new observed faults in real designs are called dynamic faults. The paper gives a mathematical analysis of such a fault class based on the fault primitive concept. The dynamic fault space will be then established; within this space dynamic functional fault models can be studied and analyzed.**

Keywords— **Memory testing, static faults, dynamic faults, fault primitive, functional fault models.**

I. INTRODUCTION

To ensure a certain DPM level, memory test engineers must use test algorithms that are able to deal with the new defects that are introduced by the new memory technologies and processes. Without such algorithms, the required DPM level, driven by market demands, can not be achieved. New systematic defects in the new memory technologies often manifest themselves in a different way than the traditional ones, hence cannot detected by the existing memory test algorithms. Adequate new fault models and (diagnosis) test algorithms are therefore essential.

Researchers studying the faulty behavior of memory devices have been defining *functional fault models (FFMs)* and developing tests to target them [5], [8], [12] [15]. However, most of the published work is limited to *static faults*, which are faults sensitized by performing *at the most* one operation; e.g., a write operation sensitizes the fault. These models were satisfactory to deal with the defects in the old technologies.

Recent published work shows that another type of faulty behavior can take place in the absence of static faults [?], HamdiouiVTS02, [10]. This faulty behavior requires *more than one operation sequentially* in order to be sensitized. For example, a write operation, followed *immediately* by a read operation, causes a cell to flip; however, if only a single write or a single read, or a read which does not immediately follow the write is performed, the cell will not flip (i.e., remain in its state). Faults requiring *more than one operation sequentially* in order to be sensitized are called *dynamic faults*. The traditional industrial memory tests are designed for static faults, and therefore may not be able to deal with the dynamic faults. In addition, [10] concludes that current and future memory products need to consider testability of dynamic faults or leave substantial DPM on table. All these indicate the importance of dynamic faults.

Research on testing of dynamic faults is in his infancy stage. The fault space and adequate fault models still remain to be established; appropriate test algorithms and test strategies still need to be designed, etc. This paper discusses the dynamic fault class based on the fault primitive concept. A fault primitive (FP) is a precise mathematical compact notation describing the faults and preventing ambiguities and misunderstanding. The FP concept will be used to define a general framework for dynamic faults with which the space of functional fault models can be studied and analyzed.

This paper is organized as follows. Section 2 introduces the concept of *fault primitives* that will be used to classify memory faults. Section 3 defines the dynamic fault space, divided into single-cell and two-cell faults. Section 4 gives the conclusions and set s direction of further research with dynamic fault framework.

II. FAULT PRIMITIVE CONCEPT AND CLASSIFICATION

This section gives first the concept of a fault primitive that will be used to define the set of the targeted FFMs in this paper. Second, a classification of memory faults will be given and used to delimit the scope of the paper.

A. Fault primitive concept

By performing a number of memory operations and observing the behavior of any component functionally modeled in the memory, functional faults can be defined as the deviation of the observed behavior from the specified one under the performed operation(s). Therefore, the two basic ingredients of any fault model are:

a. A list of performed memory operations, and
b. A list of corresponding deviations in the observed behavior from the expected one.

Any list of performed operations on the memory is called an *operation sequence*. An operation sequence that results in a difference between the observed and the expected memory behavior is called a *sensitizing operation sequence (S)*. The observed memory behavior that deviates from the expected one is called the *faulty behavior (F)*.

In order to specify a certain fault, one has to specify the S, together with the corresponding faulty behavior F and the *read result* (R) of S in case S is a read operation. The combination of S, F and R for a given memory failure is called a *Fault Primitive (FP)* [16], and is denoted as:
$< S/F/R >$. S describes the sensitizing operation sequence that sensitizes the fault (e.g., a read '0' operation from s cell containing 0 (i.e., $0r0$)), F describes the value or the behavior of the faulty cell (e.g., the cell flips from 0 to 1, while R describes the logic output level of a read operation (e.g., a wrong value 1) in case S is a read operation; this can be written as '$< 0r0/1/1 >$'.

The concept of FPs allows for establishing a complete framework of all memory faults, since for all allowed operation sequences in the memory, one can derive all possible types of faulty behavior. In addition, the concept of an FP makes it possible to give a precise definition of a *functional fault model (FFM)* as it has to be understood for memory devices [16]: *a functional fault model is a non-empty set of fault primitives.*

B. Classification

Figure 1 shows a number of different ways to classify the FPs. They can be classified based on:

1. The number of *sequential* operations required in the S, into *static* and *dynamic* faults.
2. The way the FPs manifest themselves, into *simple* and *linked* faults.

It is important to note that the three ways of classifying FPs are independent since their definition is based on independent factors of the S; see Figure 1.

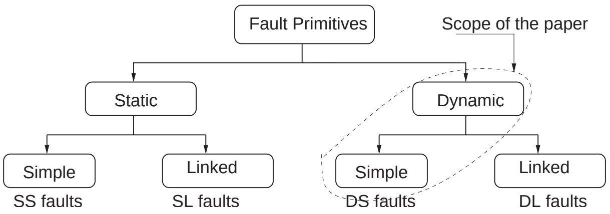

Fig. 1. Fault primitive classification

B.1 Static versus dynamic faults

Let $\#O$ be defined as the number of different operations performed *sequentially* in a S. For example, if a single read operation applied to a certain cell causes that cell to flip, then $\#O = 1$. Depending on $\#O$, FPs can be divided into *static* and *dynamic* faults:

- *Static faults*: These are FPs which sensitize a fault by performing *at the most* one operation; that is $\#O \leq 1$. For example, the state of the cell is always stuck at *one* ($\#O = 0$), a read operation to a certain cell causes that cell to flip ($\#O = 1$), etc.
- *Dynamic faults*: These are FPs that perform more than one operation *sequentially* in order to sensitize a fault; that is $\#O > 1$. Depending on $\#O$, a further classification can be made between *2-operation dynamic FPs* whereby $\#O = 2$, *3-operation dynamic FPs* whereby $\#O = 3$, etc.

B.2 Simple versus linked faults

Depending on the way FPs manifest themselves, they can be divided into *simple faults* and *linked faults*.

- *Simple faults*: These are faults which cannot be influenced by another fault. That means that the behavior of a simple fault cannot change the behavior of another one; therefore *masking* cannot occur. This paper deals with simple faults.
- *Linked faults*: These are faults that do influence the behavior of each other. That means that the behavior of a certain fault can change the behavior of another one such that *masking* can occur [13], [15], [14]. Note that linked faults consist of two or more simple faults.

A detailed analysis of static simple (SS) faults together with an appropriate test pattern is presented in [7]; the analysis of static linked (SL) faults together with their tests are presented in [11]. In the remainder of this paper, we will focus on *dynamic simple (DS)* faults; see Figure 1. From here on, the term 'fault' or 'dynamic fault' refers to a 'dynamic simple fault'.

III. DYNAMIC SIMPLE FAULT SPACE

Dynamic simple (DS) faults can be divided into FPs describing single-cell DS faults (involving a single-cell), and FPs describing multi-cell DS faults (involving more than one cell). For multi-cell FPs, we restrict our analysis to two-cell FPs, because they are considered to be an important class for memory faults [1], [2], [3], [6], [12]. Below single-cell and two-cell DS faults will be described.

A. Single-cell DS faults

Single-cell DS faults consist of FPs sensitized by applying more than one operation to a single cell *sequentially.* We will restrict our analysis to 2-operation dynamic faults, since on the one hand they already have been shown to exist [3], [9], and on the other hand the probability of dynamic faults decreases as the number of operations increases [4]. As mentioned in Section 2, a particular FP is denoted as $< S/F/R >$.

S describes the *sensitizing operation sequence*, which sensitizes a fault F in the cell. Since two operations are considered, there are 18 possible Ss. given below; $x, y, z \in \{0, 1\}$ and ‘r’ denotes a read operation and ‘w’ denotes a write operation.

- 8 Ss have the form ’$xwywz$’; e.g., ‘0w1w0’ denotes a write 1 operation applied to a cell whose initial state is 0; the write 1 operation is followed immediately with a write 0 operation.
- 2 Ss have the form ‘$xrxrx$’; e.g., ‘$0r0r0$’ denotes two successive read 0 operations applied to a cell whose initial state is 0.
- 4 Ss have the form ‘$xrxwy$’; e.g., ‘$0r0w1$’ denotes a read 0 followed immediately with write 1 applied to a cell whose initial state is 0.
- 4 Ss have the form ‘$xwyry$’; e.g., ‘$1w1r1$ denotes a write 1 followed immediately with read 1 applied to a cell whose initial state is 1.

F describes the value of the *faulty (i.e., victim)* cell (*v-cell*); $F \in \{0, 1\}$. 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: $R \in \{0, 1, -\}$. A ’$-$’ in R means that the output data is not applicable. E.g., $< 0w0w1/0/- >$; $S = 0w0w1$ cause a failing up transition write operation ($F = 0$), no data will appear at the memory output, and therefore R is replaced by a ’$-$’.

Based on the values of S, F, and R, all detectable single-cell FPs can be determined. They consist of total of 30 FPs given in Table I. The 30 FPs are compiled into a set of 5 FFMs, see also the column ‘FFM’ in the table.

1. *Dynamic Read Destructive Fault (dRDF)*: a write or a read operation followed immediately by a read operation performed on a cell changes the data in the cell, and returns an *incorrect* value on the output. The dRDF consists of six FPs; e.g., $< 0w1r1/0/0 >$: applying a ‘r1’ operation immediately after ‘w1’ operation to a cell whose initial content was 0, will cause the cell to flip to 0 and the read operation will return a wrong 0 value instead of the expected 1. The write operation involved in dRDF can be a transition write as well as a non-transition write operation.
2. *Dynamic Deceptive Read Destructive Fault (dDRDF)*: a write or a read operation followed immediately by a read operation performed on a cell changes the data in the cell, and returns a *correct* value on the output. The dDRDF consists of six FPs. Here, the write can be a transition write as well as a non-transition write operation.
3. *Dynamic Incorrect Read Fault (dIRF)*: a read operation performed *immediately* after a write or after a read operation on a cell returns an *incorrect* value on the output, while the cell remains in its correct state. The dIRF consists of six FPs.
4. *Dynamic Transition Fault (dTF)*: a transition write operation performed *immediately* after a read or after a write operation fails. The dTF consists of six FPs.
5. *Dynamic Write Destructive Fault (dWDF)*: a non-transition write operation applied *immediately* after a read or after a write operation causes the cell to flip. The dWDF consists of six FPs.

TABLE I
List of single-cell dynamic FFMs

FFM	FPs
dRDF	$< 0r0r0/1/1 >$, $< 1r1r1/0/0 >$, $< 0w0r0/1/1 >$, $< 1w1r1/0/0 >$, $< 0w1r1/0/0 >$, $< 1w0r0/1/1 >$
dDRDF	$< 0r0r0/1/0 >$, $< 1r1r1/0/1 >$, $< 0w0r0/1/0 >$, $< 1w1r1/0/1 >$, $< 0w1r1/0/1 >$, $< 1w0r0/1/0 >$
dIRF	$< 0r0r0/0/1 >$, $< 1r1r1/1/0 >$, $< 0w0r0/0/1 >$, $< 1w1r1/1/0 >$, $< 0w1r1/1/0 >$, $< 1w0r0/0/1 >$
dTF	$< 0w0w1/0/- >$, $< 1w1w0/1/- >$, $< 0w1w0/1/- >$, $< 1w0w1/0/- >$ $< 0r0w1/0/- >$, $< 1r1w0/1/- >$
dWDF	$< 0w0w0/1/- >$, $< 1w1w1/0/- >$, $< 0w1w1/0/- >$, $< 1w0w0/1/- >$, $< 0r0w0/1/- >$, $< 1r1w1/0/- >$

B. Two cell dynamic faults

Two-cell dynamic faults consist of FPs sensitized by applying more than one operation *sequentially* to two cells: the *aggressor (a-cell)* and the v-cell. The a-cell is the cell to which the sensitizing operation (or state) should be applied in order to sensitize the fault, while the v-cell is the cell where the fault appears. In a similar way as it has been done for single cell faults, we will restrict ourself to two-operation dynamic faults. Depending on how many operations are applied to the a-cell and to the v-cell, and on the order in which they are applied, four types of S can be distinguished:

1. S_{aa}: the two sequential operations are applied to the a-cell; while the v-cell is required to be in a certain state.
2. S_{vv}: the two sequential operations are applied to the v-cell; while the a-cell is required to be in a certain state.
3. S_{av}: the first operation is applied to the a-cell, followed immediately with a second one to the v-cell.
4. S_{va}: the first operation is applied to the v-cell, followed immediately with a second one to the a-cell.

Since two operations are considered, there are $18 \times 4 = 72$ total possible Ss; each S can take on one of 18 possible operation sequences: $xwywz$, $xrxrx$, $xrxwy$, or $xwyry$, where $x, y, z \in \{0, 1\}$. It is clear that despite the restriction to 2-operation dynamic faults, the number of FPs is still high. Note that S_{aa} and S_{vv} both require the access of a single cell sequentially (the v-cell, respectively the a-cell), and that S_{av} and S_{va} both require the access of two different cells sequentially.

B.1 Faults caused by S_{aa}

These faults have the property that the application of two successive operations to the a-cell will cause the v-cell to flip. To denote these faults, the FP notation: $< S_{aa}/F/R > = < S_a; S_v/F/R >$ will be used:
$S_a = yO_1zO_2t$ and $S_v = x$, where
$x, y, z, t \in \{0, 1\}$ and,
O_1 and O_2 each can be a read or a write operation.

The yO_1zO_2t denotes the sensitizing operation sequence based on two operations applied sequentially to the a-cell; x describes the *state* of the v-cell; F describes the fault effect in the v-cell; while $R = -$ since S_v requires no operation to be applied to the v-cell.

As it has been shown in the previous section, a sensitizing operation sequence based on two sequential operations applied to a single cell consist of 18 possible Ss. Therefore there are 18 possible yO_1zO_2t. The state of the v-cell (which is x) has two possibilities $x \in \{0, 1\}$. For a faulty cell, F should be $F = \overline{x}$; that means that the faults sensitized with S_{aa} can be denoted as $< yO_1zO_2t;\ x/\overline{x}/- >$; they consist of 36 PFs given in Table II, and compiled into a single FFM:

- *Dynamic Disturb Coupling Faults (CFds)*: applying two successive operations to the a-cell causes the v-cell to flip. Based on the type of the two operations, the CFds is divided into four types:

1. CFds$_{ww}$: the two operations consist of a write followed with a write. The CFds$_{ww}$ consists of 16 FPs.
2. CFds$_{wr}$: the two operations consist of a write followed with a read. The CFds$_{wr}$ consists of 8 FPs.
3. CFds$_{rw}$: the two operations consist of a read followed with a write. The CFds$_{rw}$ consists of 8 FPs.
4. CFds$_{rr}$: the two operations consist of a read followed with a read. The CFds$_{rr}$ consists of 4 FPs.

TABLE II

TWO-CELL DYNAMIC FFMS CAUSED BY S_{aa}

FFM	FP
dCFds$_{ww}$	$< 0w0w0; x/\overline{x}/- >$, $< 1w1w1; x/\overline{x}/- >$, $< 0w0w1; x/\overline{x}/- >$, $< 1w1w0; x/\overline{x}/- >$, $< 0w1w0; x/\overline{x}/- >$, $< 1w0w1; x/\overline{x}/- >$, $< 0w1w1; x/\overline{x}/- >$, $< 1w0w0; x/\overline{x}/- >$,
CFds$_{wr}$	$< 0w0r0; x/\overline{x}/- >$, $< 1w1r1; x/\overline{x}/- >$ $< 0w1r1; x/\overline{x}/- >$, $< 1w0r0; x/\overline{x}/- >$
CFds$_{rw}$	$< 0r0w0; x/\overline{x}/- >$, $< 1r1w1; x/\overline{x}/- >$, $< 0r0w1; x/\overline{x}/- >$ $< 1r1w0; x/\overline{x}/- >$
CFds$_{rr}$	$< 0r0r0; x/\overline{x}/- >$, $< 1r1r1; x/\overline{x}/- >$

B.2 Faults caused by S_{vv}

These faults have the property that the application of two successive operation to the v-cell, while the a-cell is in a certain state, sensitizes a fault in the v-cell. To denote these faults, the FP notation: $< S_{vv}/F/R > = < S_a; S_v/F/R >$ will be used. The $S_a = x$ denotes the sate of the a-cell; $x \in \{0, 1\}$. The $S_v = yO_1zO_2t$ denotes the the sensitizing operation sequence based on two operations applied sequentially to the v-cell; $y, z, t \in \{0, 1\}$ and, O_1 and O_2 can be a read or a write operation. F describes the fault effect in the v-cell; while R gives the read results in case the second operation of S_v (i.e., O_2) is a read operation.

The notation $< x; yO_1zO_2t/F/R >$ presents 60 FPs: 30 FPs denoted as $< 0; yO_1zO_2t/F/R >$ and 30 FPs as $< 1; yO_1zO_2t/F/R >$. The notation $< x; S_v/F/R >$ with $x \in \{0, 1\}$ is a superset of the notation $< S_v/F/R >$, which describe the same FPs as discussed in Section III-A and presented in Table I. The 60 FPs sensitize with S_{vv} are listed in Table III, and compiled into a set of five FFMs.

1. *Dynamic Read Destructive Coupling Fault (dCFrd)*: a write or a read followed immediately by a read operation performed on the v-cell changes the data in the v-cell and returns an *incorrect* value on the output, iff the a-cell is in a certain specific state. The dCFrd consists of 12 FPs.
2. *Dynamic Deceptive Read Destructive Coupling Fault (dCFdrd)*: a write or a read followed immediately by a read operation performed on the v-cell changes the data in the v-cell and returns a *correct* value on the output, iff the a-cell is in a certain specific state. The dCFdrd consists of 12 FPs.
3. *Dynamic Incorrect Read Coupling Fault (dCFir)*: a write or a read followed immediately by a read operation performed on the v-cell returns an *incorrect* value on the output, while the v-cell remains in its correct state, iff the a-cell is in a certain specific state. The dCFir consists of 12 FPs.
4. *Dynamic Transition Coupling Fault (dCFtr)*: a write or a read followed immediately by a *transition write* operation performed on the v-cell results in a failing write operation iff the a-cell is in a certain specific state. The dCFtr consists of 12 FPs.
5. *Dynamic Write Destructive Coupling Fault (dCFwd)*: a write or a read followed immediately by a *non transition* write operation performed on the v-cell cause that cell to flip, iff the a-cell is in a certain specific state. The dCFwd consists of 12 FPs.

TABLE III
Two-cell dynamic faults caused by S_{vv}

FFM	FPs
dCFrd	$< x; 0r0r0/1/1 >$, $< x; 1r1r1/0/0 >$, $< x; 0w0r0/1/1 >$, $< x; 1w1r1/0/0 >$, $< x; 0w1r1/0/0 >$, $< x; 1w0r0/1/1 >$
dCFdrd	$< x; 0r0r0/1/0 >$, $< x; 1r1r1/0/1 >$, $< x; 0w0r0/1/0 >$, $< x; 1w1r1/0/1 >$, $< x; 0w1r1/0/1 >$, $< x; 1w0r0/1/0 >$
dCFir	$< x; 0r0r0/0/1 >$, $< x; 1r1r1/1/0 >$, $< x; 0w0r0/0/1 >$, $< x; 1w1r1/1/0 >$, $< x; 0w1r1/1/0 >$, $< x; 1w0r0/0/1 >$
dCFtr	$< x; 0w0w1/0/- >$, $< x; 1w1w0/1/- >$, $< x; 0w1w0/1/- >$, $< x; 1w0w1/0/- >$ $< x; 0r0w1/0/- >$, $< x; 1r1w0/1/- >$
dCFwd	$< x; 0w0w0/1/- >$, $< x; 1w1w1/0/- >$, $< x; 0w1w1/0/- >$, $< x; 1w0w0/1/- >$, $< x; 0r0w0/1/- >$, $< x; 1r1w1/0/- >$

B.3 Faults caused by S_{av}

These faults have the property that the application of an operation to the a-cell, followed immediately by an operation to the v-cell, sensitizes a fault in the v-cell. To denote these faults, the FP notation: $< S_{av}/F/R > = < S_a; S_v/F/R >$ will be used. The $S_a = xO_1y$ denotes the sensitizing operation applied to the a-cell; $x, y \in \{0, 1\}$ and O_1 can be a read or a write. The $S_v = zO_2t$ denotes the sensitizing operation applied to the v-cell; $z, t \in \{0, 1\}$. The xO_1y and zO_2t each can take on one of the following *six* operation $\{0w0, 0w1, 1w0, 1w1, 0r0, 1r1\}$. F describes the fault effect in the v-cell; while R gives the read results in case the operation of S_v (i.e., O_2) is a read operation.

The faults caused by S_{av} and denoted as:
$< S_a; S_v/F/R >$ represents 60 FPs as is shown next:

- if $S_v = zwt$ $(z, t \in \{0, 1\})$,
i.e, $S_v \in \{0w0, 0w1, 1w0, 1w1\}$, then
$F = \bar{t}$ and $R = -$.
This results into 24=6×4 FPs $< S_a; zwt/\bar{t}/- >$ since S_a can take on one of the allowed six operations.

- if $S_v = yry$, i.e., $S_v \in \{0r0, 1r1\}$ then
 – if $F = y$ then $R = \overline{y}$.
This results into 12 PFs denoted as $< S_a; yry/y/\overline{y} >$.
 – if $F = \overline{y}$, then $R \in \{y, \overline{y}\}$
This results into 24=4×6 FPs: 12 denoted as
$< S_a; yry/\overline{y}/y >$ and, 12 as $< S_a; yry/\overline{y}/\overline{y} >$.

The 60 FPs are compiled into 5 FFMs each with 12 PFs; They are given in Table IV; xOy in the table denotes any operation; i.e., $xOy \in \{0w0, 0w1, 1w0, 1w1, 0r0, 1r1\}$. The names used for the FFMs here are similar to those used for FFMs caused by S_{vv}; see Section III-B.2.

TABLE IV
Two-cell dynamic faults caused by S_{av}

FFM	FPs
dCFrd	$< xOy; 0r0/1/1 >$, $< xOy; 1r1/0/0 >$
dCFdrd	$< xOy; 0r0/1/0 >$, $< xOy; 1r1/0/1 >$
dCFir	$< xOy; 0r0/0/1 >$, $< xOy; 1r1/1/0 >$
dCFtr	$< xOy; 0w1/0/- >$, $< xOy; 1w0/1/- >$
dCFwd	$< xOy; 0w0/1/- >$, $< xOy; 1w1/0/- >$

B.4 Faults caused by S$_{va}$

These faults have the property that the application of an operation to the v-cell, followed immediately by an operation to the a-cell, sensitizes a fault in the v-cell. To denote these faults, the FP notation: $< S_{av}/F/R >=< S_v/F/R; S_a >_{va}$ will be used. Note that first the v-cell has to be accessed and thereafter the a-cell. It can easily be seen that the number of FPs the notation $< S_v/F/R; S_a >_{v,a}$ represents is the same as that represented by $< S_a; S_v/F/R >_{av}$ for faults caused by S$_{av}$; the only difference is the access order of the a-cell and the v-cell. The total number of FPs presented with the notation $< S_v/F/R; S_a >_{v,a}$ is thus 60 FPs; they are compiled also into five FFMs each with 6 FPs as given in Table V. Note that the names used for the FFMs here are similar to those used for FFMs caused by S_{vv}; see Section III-B.2.

TABLE V
TWO-CELL DYNAMIC FAULTS CAUSED BY S_{va}

FFM	FPs
dCFrd	$< 0r0/1/1; xOy >$, $< 1r1/0/0; xOy >$
dCFdrd	$< 0r0/1/0; xOy >$, $< 1r1/0/1; xOy >$
dCFir	$< 0r0/0/1; xOy >$, $< 1r1/1/0; xOy >$
dCFtr	$< 0w1/0/-; xOy >$, $< 1w0/1/-; xOy >$
dCFwd	$< 0w0/1/-; xOy >$, $< 1w1/0/-; xOy >$

IV. CONCLUSIONS AND FURTHER WORK

In this paper a classification of memory cell array faults has been presented based on the fault primitive concept. Special attention has been given to dynamic faults. A complete framework for two-operations dynamic faults, based on the fault primitive concept, has been presented. Within this framework, the space of dynamic faults can be (experimentally) studied and analyzed.

Dynamic fault class which has been ignored in the past are now becoming very important for the new memory technologies. This sets a new direction for further research on memory fault modeling. Items like the following remain still to be worked out:

1. In order to investigate their validity, and experimental and/or industrial analysis is required. This can be done based on defect injection and SPICE simulation.
2. Inductive Fault Analysis in order to determine the importance of each introduced fault model and to better understand the underlying defects causing such dynamic faults.
3. Design of short and high quality tests targeting and diagnosing the considered dynamic faults. This will reduce the DPM level of the new memory technologies and improve the yield.
4. Industrial validation of the tests in high volume production.

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