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\newcommand{\beq}{\begin{equation}}
\newcommand{\eeq}{\end{equation}}
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\newtheorem{lemma}{Lemma}[section]
\newtheorem{theorem}{Theorem}[section]
\newtheorem{corollary}{Corollary}[section]
\newtheorem{remark}{Remark}[section]
\newtheorem{example}{Example}[section]
\newtheorem{stage}{Stage}[section]
\title{Pseudo-exhaustive Word-Oriented DRAM Testing}

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\begin{document}
\maketitle

\begin{center}
  {\bf Abstract}
\end{center}
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\noindent This paper presents a new methodology for RAM testing based
on the $PS(n, k)$ $q$-ary fault model which includes most classical fault
models for SRAMs and DRAMs.  According to this fault model, the
contents of any $w$-bit memory word of a memory with $n$ words, or
ability to change this contents, is influenced by the contents of any
other $k-1$ words of the memory.  The proposed methodology uses a
pseudo-exhaustive technique based on {\em Reed-Solomon} codes, which
can be efficiently applied to a word-oriented RAMs, assuming small
values of $k$. The methodology ensures the detection of any number of
disjoint (not linked) $k$ coupling faults, whereby the involved $k$
words may be located anywhere in the memory; i.e., no assumptions have
to be made on the physical topology of the cells in the memory cell
array. Because of the systematic structure of the proposed tests, they
are well suited for BIST implementations. \\
\\
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\noindent
{\bf Key words:} Memory testing, pattern sensitive faults,
pseudo-exhaustive memory testing, random access memory.
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\section{Introduction}
\label{sec:sec1}

The increasing densities in memory technology has resulted in a
dramatically increasing test cost [1,2] caused by the increased number
of cells to be tested, as well as the more complex fault models. The latter
applies especially to DRAMs, where in addition to the traditional
faults for SRAM chips [3,4], neighborhood pattern sensitive faults
'NPSFs' [5-8] have to be considered.

The well-known tests for NPSFs usually require that the physical
topology of the cells in the memory cell array is known, while they
assume that the memory words usually consist of a single bit. In
addition, tests for NPSFs do not detect many of the classical faults
which also apply to SRAMs [3]; e.g., address decoder faults 'AFs',
data retention faults 'DRFs' [9], stuck-open faults 'SOFs' [9], and
coupling faults. Pseudo-random memory tests [10,11] do not require
knowledge of the physical topology of the memory cell array and can be
applied to memories with $w$-bit words ($w \geq 2$); however, they have the
disadvantage that their fault coverage is probalistic. The capability
of a test to cope with memories with $w$-bit words ($w \geq 2$) is of
increasing importance; whereas early memory chips has a $n \ast 1$
(where $n$ is the number of words) organization, currently many chips
have a $n \ast 4$ organization while $n \ast 8$ chips are expected to
reach high volume production soon [13].

This paper proposes a new fault model which has the following
properties:
\begin{enumerate}
\item It is modular in terms of $k$, the number of words involved in
  the fault.
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\item Words are $w$-bits ($w \geq 1$) wide.
\item No assumptions have to be made on the physical location of the
  $k$ words.
\item It includes many of the traditional SRAM and DRAM faults.
\end{enumerate}

The organization of this paper is as follows: Section \ref{sec:sec2}
introduces the fault model, Section \ref{sec:sec3} describes the test
approach which is based on pseudo-exhaustive testing, Section
\ref{sec:sec4} gives the mathematical background for the proposed
tests, Section \ref{sec:sec5} describes the pseudo-exhaustive tests,
and Section \ref{sec:sec6} concludes this paper.



\section{Fault model}
\label{sec:sec2}

This section describes the new fault model for pseudo-exhaustive
testing of DRAMs. First, the fault models used for testing SRAMs,
together with an explanation concerning their applicability to DRAMs,
will be presented. Next, the classical DRAM fault models are
presented. And last, the new $PS(n,k)$ $q$-ary fault model will be
introduced; it will be shown which of the classical SRAM and DRAM
fault models it covers; for those faults, considered important for
DRAMs, which are not covered by the new fault
model a separate set of tests will be proposed.


\subsection{Classical SRAM fault models}
\label{sec:sec21}

The classical SRAM faults which have been found to be important [4,9]
are listed below; a motivation is given when they do not appy to
DRAMs.
\begin{itemize}
\item Stuck-at fault 'SAF'.
\item Stuck-open fault 'SOF' [9] \\
  SRAMs need special test provisions to cope with SOFs when the sense
  amplifiers are not transparent to SOFs. In case of DRAMs this
  problem does not occur because the differential sense amplifier has
  only one input from the cell being read such that SOFs behave as
  SAFs.
\item Transition faults 'TFs'\\
  These faults cannot occur in the memory cell array of the DRAM
  because the cells are not implemented as bi-stable elements.
\item Coupling faults 'CFs' \\
  The CFs of interest are the idempotent CF 'CFid'' and the state CF
  'CFst' [9].
\item Data retention faults 'DRFs' [9] \\
  The SRAM type of DRFs cannot occur in DRAMs because of the absense
  of pull-up devices. However, leakage currents may cause loss of
  information. A refresh test, using a checkerboard pattern, has to be
  used for this [3].
\item Address decoder faults 'AFs'.
\end{itemize}

Considering the above, the SRAM faults which also apply to DRAMs are
the SAFs, the CFs and the AFs.
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\subsection{Classical DRAM faults}
\label{sec:sec22}

Pattern sensitive faults 'PSFs' [5-8,3] are considered typical for
DRAMs. They involve a group of $k$ cells whereby $k-1$ cells influence
a given target cell, called the {\em base cell}. In order to keep the
test time within acceptable limits for larger chips, the assumption is
made that the $k-1$ cells, which influence the base cell, physically
surround the base cell; this simplifies the PSF model to a
neighborhood PSF 'NPSF' model; the $k-1$ cells
influencing the base cell are called the deleted neighborhood
cells. This is a realistic simplification because of the underlying
assumption that PSFs are caused by leakage  currents which can only
occur between cells in a physical neighborhood. The disadvantage of
the NPSF model is that the physical topology of the cells in the
memory cell array has to be known; this is not always so: the use of
spare rows and columns already violates this, even for tests performed
by the manufacturer; the user usually does not have access to the
physical topology which, in addition, may differ between functionally
equivalent parts of different manufacturers.

The classical NPSFs usually considered are [3]:
\begin{itemize}
\item Active NPSF 'ANPSF' [8]  \\
  The base cell changes its contents due to a change in the $k-1$
  deleted neighborhood patterns (i.e. the value of the $k-1$ cells).
\item Passive NPSF 'PNPSF' [12] \\
  The content of the base cell cannot be changed due to a certain
  deleted neighborhood pattern.
\item Static NPSF 'SNPSF' [8] \\
  The base cell is forced to a certain state due to a certain deleted
  neighborhood pattern.
\end{itemize}


\subsection{The $PS(n,k)$ $q$-ary fault model}
\label{sec:sec23}

Given a memory with $n$ words consisting of $w$-bits whereby $q$ is
defined as $q = 2^w$. Then the following fault definitions can be given.

\begin{enumerate}
\item {\em Stuck-at $q$-ary faults 'SAFq'} \\
  A permanent stuck-at
  $q$-ary fault reduces the number of faulty memory word states. A
  faulty word $i$ of the memory may contain the only one $q$-ary
  digit, or a subset $S$ of all possible $q$-ary digits $0,1,2,\ldots ,
  q-1$. This fault model covers the classical SAFs.

\item {\em Transition $q$-ary faults 'TFq'} \\ A memory word $i$ in
  the state $W_{i}(t)\in \{0,1,\ldots , q-1\}$ fails to undergo an
  $W_{i}(t)$ to ${W}_{i}(t+1)$ transition when $W_{i}(t)\neq
  {W}_{i}(t+1)$ (whereby $W_{i}(t)$ and ${W}_{i}(t+1)\in
  \{0,1,2,\ldots ,q-1\}$) and ${W}_{i}(t+1)$ is to be written in the
  $i$-th memory word; however, both states are possible for the $i$-th
  memory word, for instance at power-on time. This fault model covers
  the classical TFs.

\item {\em Coupling $q$-ary faults 'CFq'} \\ A coupling $q$-ary fault
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  is present from a memory word $i$ to a word $j$ if, when the words
  contain a particular pair of $q$-ary values $W_{i}(t)$ and
  $W_{j}(t)$, and ${W}_{i}(t+1)$ is written into word $i$, then word
  $j$, as well as word $i$, change state. This fault model covers the classical
  CFids and CFsts.

\item {\em Pattern sensitive q-ary faults 'PSFq'\/} \\
  The base word changes its contents, or cannot be changed, due to a
  pattern, or a change, in the $k-1$ other words. This definition
  covers the classical NPSFs of Section \ref{sec:sec22}.
\end{enumerate}

\noindent
The above 4 fault models are covered by the $PS(n,k)$ $q$-ary fault
model, which has the following properties:
\begin{enumerate}
\item $k$ $w$-bit words, whereby each word can be in $q$ ($q = 2^w$)
  states, are involved in the fault model.
\item the base word will take on all $2^w$ states and each cell in the
  base word will make an up and a down transition for each of
  $2^{w-1}$ states of the $w-1$ other cells in the word.
\item each of the $k-1$ non-base words will take on all $2^{w}$ states
  for each state or transition of the base word.
\end{enumerate}
For any one of 2^{(k-1)w} internal states of k-1 nonbase words all 2^{2w}
transitions in the base cell may occur.
The above fault model will detect the 4 $q$-ary faults:
\begin{enumerate}
\item $SAFq$ and $TFq$ faults will be detected because of property 1.
\item $CFq$ faults will be detected because of property 1 and 2 for $k
  \geq 2$.
\item $PSFq$ faults will be detected because of properties 1 through 3
  and $k = k$.
\end{enumerate}



\section{Pseudo-exhaustive memory testing}
\label{sec:sec3}

Pseudo-exhaustive testing [14] of combinational devices has
several attractive features. In addition to the fact that test
patterns can be generated quite easily, the process and its fault
coverage are basically dependent neither on the fault model assumed
nor on its specific circuit under test.

Let us give some basic definitions of pseudo-exhaustive memory testing.
\begin{definition}
\begin{rm}
  A background for a $(w\times n)$ memory ($w$-bits per word, $n$
  words) is a vector $B=(B^{(0)}, B^{(1)}, \ldots , B^{(n-1)})$, where
  $B^{(j)}\in GF(2^w)$, $j\in \{0,1,2,\ldots ,n-1\}$ and $GF(2^w)$ is
  the field of $w$-dimensional binary vectors.$\Box$
\end{rm}
\end{definition}
\begin{definition}
\begin{rm}
  A $k$-pseudo-exhaustive backgrounds is a matrix $B(n,k,w)$, where
  rows are backgrounds $B_i=(B_{i}^{(0)},B_{i}^{(1)}, \ldots
  ,B_{i}^{(n-1)}), B_{i}^{(j)}\in GF(2^w);~ i=0,1,\ldots ,T_k-1;~
```

```
  j=0,1,\ldots , n-1$ such that in the matrix $B(n,k,w)$ all $q^k$
  $k$-digit $q$-ary $(q=2^w)$ vectors $(y_0,y_1,\ldots ,y_{k-1})$
  (where $y_l\in GF(2^w), l=0,1,\ldots ,$ $k-1$) appear at least once
  in any $k$ columns.$\Box$
\end{rm}
\end{definition}

By the definition of $k$-pseudo-exhaustive backgrounds $B(n,k,w)$ we
have the lower bound on the number $T_k=T_k(n)$ of backgrounds
$T_k(n)\geq q^{k}=2^{wk}$.

Techniques for construction of $k$-pseudo-exhaustive data backgrounds
$B(n,k,w)$ and estimations on minimal numbers of pseudo-exhaustive
patterns can be found for the binary case $(w=1)$ in [14].
Techniques for construction of $k$-pseu\-do-exhaustive data
backgrounds $B(n,k,w)$ and estimations on their minimal sizes for the
$q$-ary case $(w>1)$ are not known. We will present in this paper
optimal solutions, satisfying to the lower bound, of this problem for
small $k$.


As a systematic approach for $k$-pseudo-exhaustive data backgrounds
generation we propose to use {\em Reed-Solomon} codes over $GF(2^w)$
[15].


The extended $(q+1,q+1-k,k+1)$ {\em Reed Solomon (RS)} code over
$GF(2^w)$ is defined by the check matrix \cite{MAC77}:
\begin{equation}
H=
\left |
\begin{array}{lllllll}
1 & 0 & 1 & 1 & 1 & \ldots & 1  \\
0 & 0 & 1 & \alpha & \alpha^{2} & \ldots & \alpha^{q-2} \\
0 & 0 & 1 & \alpha^{2} & \alpha^{4} & \ldots & \alpha^{2(q-2)} \\
\dots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots  \\
0 & 1 & 1 & \alpha^{k-1} & \alpha^{2(k-1)} & \ldots & \alpha^{(k-1)(q-2)}
\end{array} \right | ,
\label{eq:3a}
\end{equation}
where $\alpha$ is primitive in $GF(2^w)$ ($\alpha^i \neq \alpha^j$ for
$i\neq j \in \{0, 1, \ldots ,q-2 \}$). Since any $k$ columns of $H$
are linearly independent over $GF(q)$, the linear span of rows of $H$
will be an optimal $k$-pseudo-exhaustive background $B(2^w+1,k,w)$
with $T_k=q^k=2^{wk}$.
\begin{example}
\begin{rm}
\label{ex:4}
Let $q=2^{w}=4$ and $GF(2^{2})=\{0, 1, \alpha, \alpha^{2} \}$, where
$\alpha$ is a root of polynomial $\varphi (x)=x^{2} + x + 1$~
$(\alpha^3 = 1)$, then the operations of addition and multiplication
in the field $GF(2^{2})$ described by the following tables.
\begin{center}
%\caption{Addition (+)}
\begin{tabular}{c||c|c|c|c}
\multicolumn{5}{c}{Addition (+)} \\
 $0$      &  $0$      &  $1$ & $\alpha$  & $\alpha^{2}$ \\
 $1$      &  $1$      &  $0$ & $\alpha^{2}$  & $\alpha$ \\
 $\alpha$ &  $\alpha$ &  $\alpha^{2}$ & $0$  & $1$ \\
 $\alpha^{2}$ & $\alpha^{2}$ &  $\alpha$ & $1$  & $0$
```

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\end{tabular}
%\end{center}
~~~~~~~~~~
%\begin{center}
%\caption{Multiplication ($\times$)}
%\label{tbl:4a}
\begin{tabular}{c||c|c|c|c}
\multicolumn{5}{c}{Multiplication ($\times$)} \\
 $0$      &  $0$      &  $0$ & $0$  & $0$ \\
 $1$      &  $0$      &  $1$ & $\alpha$  & $\alpha^{2}$ \\
 $\alpha$ &  $0$      &  $\alpha$ & $\alpha^{2}$  & $1$ \\
 $\alpha^{2}$ & $0$   &  $\alpha^{2}$ & $1$  & $\alpha$
\end{tabular}
\end{center}
where $0=00, 1=10, \alpha=01$, $\alpha^2=11$, $\alpha^3 = 1 =
10$, $\alpha^4 = \alpha = 01$.

For the construction of the optimal 2-pseudo-exhaustive backgrounds
over $GF(2^2)$ we use the check matrix $H$. Then, any background
$B=(B^{(0)},B^{(1)},B^{(2)},B^{(3)},B^{(4)})$ can be generated as
\begin{equation}
(v_0, v_1)
\cdot
\left |
\begin{array}{ccccc}
1 & 0 & 1 & 1 & 1  \\
0 & 1 & 1 & \alpha & \alpha^{2}
\end{array} \right |
=(v_0, v_1, v_0+v_1, v_0+\alpha v_1, v_0+\alpha^2 v_1),
\label{eq:4z}
\end{equation}
where $v_0, v_1 \in GF(2^2)$.

For example, $(\alpha, \alpha^{2}) \left |
\begin{array}{ccccc}
1 & 0 & 1 & 1 & 1 \\
0 & 1 & 1 & \alpha & \alpha^2
\end{array}
\right |
= (\alpha, \alpha^2, \alpha + \alpha^2, \alpha + \alpha^3, \alpha +
\alpha^4 ) = \alpha, \alpha^2, 1, \alpha^2, 0)$ or in the binary
notation:

\begin{equation}
  (01,11) \left |
  \begin{array}{ccccc}
    10 & 00 & 10 & 10 & 10 \\
    00 & 10 & 10 & 01 & 11
  \end{array}
\right |
= (01, 11, 10, 11, 00)
\end{equation}


As a result of multiplication of all vectors $V=(v_{0},~v_{1})$ by $H$
we have 2-pseudo-ex\-haus\-tive data backgrounds $B(5,2,2)$ (see
Table~\ref{tbl:os}).
\begin{table}
\caption{2-Pseudo-exhaustive  backgrounds $B(5,2,2)$}
\begin{center}
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\label{tbl:os}
{\small
\begin{tabular}{r||c||cc||ccccc}  \hline \hline
$i$ & $\beta^{i-1}$ & $v_{0}(i)$ & $v_{1}(i)$ & $B_{i}^{(0)}$    & $B_{i}^{(1)}$ & $B_{i}^{
$-$ & $-$ & $0$       &  $0$  &  $0$   & $0$   &  $0$   &   $0$   & $0$ \\
$1$ & $\beta^{0}$ & $1$       &  $0$  &  $1$   & $0$  &  $1$   &    $1$   & $1$  \\
$2$ & $\beta^{1}$ & $0$       &  $1$  &  $0$   & $1$   &  $1$   &    $\alpha$   & $\alpha^2$
$3$ & $\beta^{2}$ & $\alpha$      &$1$ &  $\alpha$ & $1$ & $\alpha^2$  & $0$ &  $1$ \\
$4$ & $\beta^{3}$ & $\alpha$&$\alpha^2$ &  $\alpha$ &  $\alpha^2$ & $1$  & $\alpha^2$ &  $(
$5$ & $\beta^{4}$ & $1$&$1$ &  $1$ & $1$ & $0$  & $\alpha^2$ &  $\alpha$ \\
$6$ & $\beta^{5}$ & $\alpha$&$0$ &  $\alpha$  & $0$ & $\alpha$  & $\alpha$ &  $\alpha$ \\
$7$ & $\beta^{6}$ & $0$&$\alpha$ &  $0$ &  $\alpha$ & $\alpha$  & $\alpha^2$ &  $1$ \\
$8$ & $\beta^{7}$ & $\alpha^2$&$\alpha$ &  $\alpha^2$ &  $\alpha$  & $1$  & $0$ &  $\alpha$
$9$ & $\beta^{8}$ & $\alpha^2$&$1$ &  $\alpha^2$ & $1$ & $\alpha$  & $1$ &  $0$ \\
$10$ & $\beta^{9}$ & $\alpha$&$\alpha$ &  $\alpha$ &  $\alpha$ & $0$  & $1$ &  $\alpha^2$ \
$11$ & $\beta^{10}$ & $\alpha^2$&$0$ &  $\alpha^2$ & $0$ & $\alpha^2$  & $\alpha^2$ &  $\al
$12$ & $\beta^{11}$ & $0$&$\alpha^2$ &  $0$ &  $\alpha^2$ & $\alpha^2$  & $1$ &  $\alpha$ \
$13$ & $\beta^{12}$ & $1$&$\alpha^2$ &  $1$ &  $\alpha^2$ & $\alpha$  & $0$ &  $\alpha^2$ \
$14$ & $\beta^{13}$ & $1$&$\alpha$ &  $1$ &  $\alpha$ & $\alpha^2$  & $\alpha$ &  $0$ \\
$15$ & $\beta^{14}$ & $\alpha^{2}$ & $\alpha^{2}$ & $\alpha^2$ & $\alpha^{2}$ & $0$  & $\al
$16$ & $\beta^{1}$ & $1$       &  $0$  &  $1$ & $0$ &  $1$   &    $1$   & $1$
\end{tabular}
}
\end{center}
\end{table}
As we can see from Table~\ref{tbl:os} for any $k=2  ~~ q=2^2$-ary words we have all $q^2=(2
\end{rm}
\end{example}

We will describe in the following sections test procedures based on
$k$-pseudo-exhaus\-tive data backgrounds $B_{0},B_{1},\ldots
,B_{q^k-1}$, combined with the standard $MATS+$ test (to cover AFs)
[4] for $k=1,2$ and $3$.

\section{Mathematical background}
\label{sec:sec4}

The following theorem can be used for construction of $k$-pseudo-exhaustive backgrounds for
\begin{theorem}
\begin{rm}
Let $q=2^{w},$ $\alpha$ is primitive in $GF(q)$ $(\alpha^{l}\neq \alpha^{j}; l\neq j; l,j=(
\begin{equation}
H=
\left |
\begin{array}{lllll}
 1 & 1 & 1 & \ldots & 1 \\
 1 & \alpha & \alpha^{2} & \ldots & \alpha^{q-2} \\
 1 & \alpha^{2} & \alpha^{4} & \ldots & \alpha^{2(q-2)} \\
\ldots & \ldots & \ldots & \ldots & \ldots  \\
 1 & \alpha^{k-1} & \alpha^{2(k-1)} & \ldots & \alpha^{(k-1)(q-2)}
\end{array} \right |
\label{eq:ap1}
\end{equation}

Denote
\begin{equation}
\beta^{i-1}=(\alpha^{i_{0}},\alpha^{i_{1}},\ldots ,\alpha^{i_{k-1}}) \in GF(q^{k}),
\label{eq:a1}
\end{equation}
and $B_{0}=(0,0,\ldots , 0),$ $ B_{i}=(B_{i}^{(0)},B_{i}^{(1)},$
```

```
$\ldots , B_{i}^{(q-1)})$ = $(\alpha^{i_{0}},\alpha^{i_{1}},\ldots
,\alpha^{i_{k-1}})H$ $(B_{i}^{(j)}\in {GF(q)}, i=1,2,\ldots ,q^{k})$.
Then,
\begin{enumerate}
\item For any $j_{0}\leq j_{1}\leq \ldots \leq j_{k-1}$ and any $A_{j_{0}}, A_{j_{1}}, \ldo
\begin{eqnarray*}
B_{i}^{(j_{0})}=A_{j_{0}},~ B_{i}^{(j_{1})}=A_{j_{1}},\ldots ,~B_{i}^{(j_{k-1})}=A_{j_{k-1}
\end{eqnarray*}
\item For any $s\in \{0,1,\ldots ,q-2 \}$, $j_{0}\leq j_{1}\leq \dots \leq j_{k-3}$ $(s\not
 there exists $i\in \{1,2,\ldots ,q^{k} \}$ such that
\begin{equation}
B_{i}^{(j_{0})}=A_{j_{0}},~ B_{i}^{(j_{1})}=A_{j_{1}},\ldots, B_{i}^{(j_{k-3})}=A_{j_{k-3}}
\label{eq:yy1}
\end{equation}
$\Box$
\end{enumerate}
\label{te:1}
\end{rm}
\end{theorem}
\begin{remark}
\begin{rm}
\label{rm:r1}
Theorem~\ref{te:1} is valid for more general case when for any subset
$J$ of $\{j_{0},j_{1},\ldots ,j_{k-3}\}$ in~(\ref{eq:yy1}) $B_{i}^{(j)}$ is replaced by  $B
\end{rm}
\end{remark}
\begin{remark}
\begin{rm}
\label{rm:r2}
Theorem~\ref{te:1} and Remark~\ref{rm:r1} is valid for $k=2$ and $n=q+1$ when we use the ch
\begin{equation}
H=
\left |
\begin{array}{lllllll}
1 & 0 & 1 & 1 & 1 & \ldots & 1 \\
0 & 0 & 1 & \alpha & \alpha^{2} & \ldots & \alpha^{q-2} \\
0 & 0 & 1 & \alpha^{2} & \alpha^{4} & \ldots & \alpha^{2(q-2)} \\
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots  \\
0 & 1 & 1 & \alpha^{k-1} & \alpha^{2(k-1)} & \ldots & \alpha^{(k-1)(q-2)}
\end{array} \right |
\label{eq:apn1}
\end{equation}
of the $[q+1,q+1-k,k]$ MDS code~\cite{MAC77} instead of $H$ defined by(~\ref{eq:ap1}).$\Box
\end{rm}
\end{remark}
\begin{remark}
\begin{rm}
\label{rm:r3}
Theorem~\ref{te:1} is valid for any $k$ and $n=q$ when check matrix
\begin{equation}
H=
\left |
\begin{array}{llllll}
1 & 1 & 1 & 1 & \ldots & 1 \\
0 & 1 & \alpha & \alpha^{2} & \ldots & \alpha^{q-2} \\
0 & 1 & \alpha^{2} & \alpha^{4} & \ldots & \alpha^{2(q-2)} \\
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots  \\
0 & 1 & \alpha^{k-1} & \alpha^{2(k-1)} & \ldots & \alpha^{(k-1)(q-2)}
\end{array} \right |
\label{eq:apn2}
```

```
\end{equation}
represents the $[q,q-k,k]$ MDS code.$\Box$
\end{rm}
\end{remark}


By the Theorem~\ref{te:1} and Remarks~\ref{rm:r1},~\ref{rm:r2} and
\ref{rm:r3} $k$-pseudo-exhaustive backgrounds, defined
by~(\ref{eq:ap1}),~(\ref{eq:a1}), combined with $MATS+$ procedure
generate optimal tests with $q^k=2^{wk}$ backgrounds and with
complexity $2^{wk+1}n$ detecting static $SPS(n,k)$ faults and dynamic
$DPS(n,k-1)$ faults for any $k>2$ for $n<2^w$; for $k=2$ and
$n=2^w+1$; and detecting $SPS(n,k)$ for any $k$ and $n=2^w$. In the
next sections we will expand these procedures for the cases $n>2^w$
and $k=1,2,3$.


\section{Pseudo-exhaustive memory tests}
\label{sec:sec5}
\subsection{k-Pseudo-exhaustive backgrounds}
\label{sec:sec51}

For the case $k=1$ the procedure for generation of 1-pseudo-exhaustive
backgrounds consists of multiplication in $GF(2^w)$ of all $q$-ary
vectors $V=(v_{0})$, $v_{0}\in \{0,1,$ $\alpha,$ $\alpha^{2}$, $\ldots
,\alpha^{q-2}\}$ by the first row of the {\em RS} check
matrix~(\ref{eq:3a}). The row dimension is determined by the memory
size $n$. As a result we will have the $B(n,1,w)$ optimal
1-pseudo-exhaustive backgrounds with $T_1(n)=q$ for any $n$.


For example, for a 2-bit wide memory with 6 cells ($w = 2$, $q = 4$,
$n = 6$) we have the following backgrounds $B(6,1,2)$:

\[
\begin{array}{ccc}
\begin{array}{|c|c|c|c|c|c|}
\hline
B_0 & B_1 & B_2 & B_3 & B_4 & B_5  \\
\hline \hline
0 & 0 & 0 & 0 & 0 & 0  \\
1 & 1 & 1 & 1 & 1 & 1  \\
\alpha & \alpha & \alpha & \alpha & \alpha & \alpha  \\
\alpha^2 & \alpha^2 & \alpha^2 & \alpha^2 & \alpha^2 &
\alpha^2  \\
\hline
\end{array}
&
=
&
\begin{array}{|c|c|c|c|c|c|}
\hline
B_0 & B_1 & B_2 & B_3 & B_4 & B_5  \\
\hline \hline
00 & 00 & 00 & 00 & 00 & 00  \\
10 & 10 & 10 & 10 & 10 & 10  \\
01 & 01 & 01 & 01 & 01 & 01 \\
11 & 11 & 11 & 11 & 11 & 11 \\
\hline
\end{array}
```

```
\end{array}
\]

For the complexity of the test procedure based on $B(n,1,w)$ and MATS+
we have \linebreak $L[MATS+, B(n,1,w)] = 2^{w+1}n$.

More complex is a procedure of the background generation for $k=2$.
Let $\varphi (x)=x^2 + c_1x + c_0$ ~ $(c_0,c_1\in GF(2^w))$ be a
primitive polynomial of degree 2 over $GF(2^w)$ and $\beta $ is a root
of $\varphi (x) $ $(\varphi(\beta)=0)$. Then~\cite{MAC77}, there
exists a one-to-one mapping $i \leftrightarrow (v_0(i),v_1(i))$,
where $v_0(i),v_1(i) \in \{1,\alpha,\alpha^2,\ldots ,\alpha^{q-2}\}$
($v_0(i),v_1(i))\neq (0,0)$; $i \in \{1,2,\ldots ,q^2\}$; and $q=2^w$,
such that
\begin{equation}
v_0(i)+v_1(i)\beta = \beta^{i-1},
\label{eq:yz}
\end{equation}
where $\beta^{q^{2}-1}=\beta^0=1$.
This mapping for $w=2$ and $\varphi(x)=x^2+x+\alpha$ is given in Table~\ref{tbl:os}.

According to the procedure  for $n=q+1$ described by the Remark~\ref{rm:r2} for generation
\begin{equation}
B_i^{(j)}=B(q+1,2,w) =  |v_{0}(i), v_{1}(i)|\cdot
\left |
\begin{array}{llllllll}
1 & 0 & 1 & 1 & 1 & \ldots & 1 & 1  \\
0 & 1 & 1 & \alpha & \alpha^{2} & \ldots & \alpha^{q-4} & \alpha^{q-2}
\end{array} \right |.
\label{eq:9a}
\end{equation}

Thus, $B_{0}=(0,0,\ldots, 0)$  $B^{(0)}_{i}=v_{0}(i)$,  $B^{(1)}_{i}=v_{1}(i)$,  $B^{(j)}_{


Any set $B(q+1,2,w)$ of 2-pseudo-exhaustive  backgrounds consists of the $T_2(q+1)=2^{2w}+1

For the complexity of the test procedure based on 2-pseudo-exhaustive
backgrounds $B(n,2,w)$ and MATS+ we have $L(MATS+ B(n,2,3)) = 2 (q^2 +
1)n = 2^{2w+1}n + 2n$.

For any $k$ the procedure for generating $k$-pseudo-exhaustive
backgrounds will be described the following way.  Let $\varphi (x)$ be
a primitive polynomial of degree $k$ over $GF(2^w)$ and $\beta $ is a
root of $\varphi (x) $ $(\varphi(\beta)=0)$. Then~\cite{MAC77}, there
exists an one-to-one mapping $i \leftrightarrow (v_0(i),v_1(i),\ldots
,v_{k-1}(i))$, where $v_0(i),v_1(i),\ldots ,v_{k-1}(i) \in
\{1,\alpha,\alpha^2,\ldots ,\alpha^{q-2}\}$ ($v_0(i),v_1(i),\ldots
,v_{k-1}(i))\neq (0,0,\ldots ,0)$; $i \in \{1,2,\ldots ,q^k\}$; and
$q=2^w$, such that
\begin{equation}
v_0(i)+v_1(i)\beta +\ldots + v_{k-1}(i)\beta^{k-1} = \beta^{i-1},
\label{eq:yzy}
\end{equation}
where $\beta^{q^{2}-1}=\beta^0=1$.

According to the procedure for $n=q-1$ described by the
Theorem~\ref{te:1} for the generation of optimal $k$-pseudo-exhaustive
backgrounds we have $B(q-1,k,w)$, where $T_{k}(q)=q^k+1$;
$(B^{(j)}_{i} \in GF(2^w), q=2^w)$, $B^{(j)}_{0}=0, (j=0,1,\ldots,q)$,
```

```
\begin{equation}
B_i^{(j)}=  |v_{0}(i), v_{1}(i), \ldots , v_{k-1}(i)|\cdot
\left |
\begin{array}{llllll}
1 & 1 & 1 & \ldots & 1 & 1  \\
1 & \alpha & \alpha^{2} & \ldots & \alpha^{q-4} & \alpha^{q-2} \\
1 & \alpha^2 & \alpha^{4} & \ldots & \alpha^{2(q-4)} & \alpha^{2(q-2)} \\
\ldots & \ldots & \ldots & \ldots & \ldots &\ldots \\
1 & \alpha^{k-1} & \alpha^{2(k-1)} & \ldots & \alpha^{(k-1)(q-4)} & \alpha^{(k-1)(q-2)}
\end{array} \right |.
\label{eq:9ay}
\end{equation}

Any set $B(q-1,k,w)$ of $k$-pseudo-exhaustive  backgrounds consists of the $T_k(q-1)=2^{kw}

\subsection{Restricted pseudo-exhaustive tests $RPST_{k,k-1}$}


Generalization of the tests for detection of crosstalks between three
or more words will require high complexity and considerable overheads
for BIST implementations. In view of this we describe in this
section a class of restricted (local) pseudo-exhaustive tests
$RPXT_{k,k-1}, (k=2,3,4,...)$ for word-oriented memories detecting
static $SPS(q-1,k)$ and dynamic $DPS(q-1,k-1)$ faults due to
crosstalks between $k$ or $k-1$ words within any block of $q-1$
neighbouring words.

To construct these tests we use $k$-pseudo-exhaustive backgrounds $B(q-1,k,w)$ described ir

At the first step of $RPXT_{k,k-1}$ we run pseudo-exhaustive tests  $PXT_{k,k-1}$ based on


This approach is illustrated in Fig.~\ref{fig:di}.



%          ****************************************
%                          Fig. {fig:di}
%          ****************************************

\begin{figure}

\begin{center}
\unitlength1mm
\begin{picture}(140,80)


\thicklines
\put(20,55){\line(1,0){120}}
\multiput(20,56)(120,0){2}{\line(0,-1){2}}
\multiput(20,45)(17,-10){3}{\line(1,0){30}}
\multiput(20,46)(17,-10){3}{\line(0,-1){2}}
\multiput(50,46)(17,-10){3}{\line(0,-1){2}}
\put(130,10){\line(1,0){10}}
\put(20,10){\line(1,0){20}}
\put(130,11){\line(0,-1){2}}
\put(140,11){\line(0,-1){2}}
\put(20,11){\line(0,-1){2}}
\put(40,11){\line(0,-1){2}}
```

```
\thinlines
\multiput(20,45)(30,0){2}{\line(0,1){15}}
\multiput(37,35)(30,0){2}{\line(0,1){27}}
\multiput(54,25)(30,0){2}{\line(0,1){40}}
\multiput(130,10)(10,0){2}{\line(0,1){50}}


\put(10,45){\makebox(0,0){\scriptsize$Step 1$}}
\put(10,35){\makebox(0,0){\scriptsize$Step 2$}}
\put(10,25){\makebox(0,0){\scriptsize$Step 3$}}
\put(10,17){\makebox(0,0){\scriptsize$\ldots$}}
\put(105,17){\makebox(0,0){\scriptsize$\ldots$}}
\put(10,10){\makebox(0,0){\scriptsize$Step \lceil \frac{n}{q-1} \rceil$}}

\put(20,63){\makebox(0,0){\scriptsize$0$}}
\put(50,63){\makebox(0,0){\scriptsize$2^w-1$}}
\put(37,65){\makebox(0,0){\scriptsize$2^{w-1}$}}
\put(54,68){\makebox(0,0){\scriptsize$2^w$}}
\put(67,65){\makebox(0,0){\scriptsize$2^{w-1} +2^w-1$}}
\put(84,68){\makebox(0,0){\scriptsize$22^w-1$}}
\put(130,63){\makebox(0,0){\scriptsize$n-2^w+1$}}
\put(140,63){\makebox(0,0){\scriptsize$n$}}


\end{picture}
\end{center}

\caption{Test Organization for $RPXT_{k,k-1}$}
\label{fig:di}
\end{figure}

Test $RPXT_{2,1}$ for $w=2$ $(q=4)$, $n=5$ consisting of two steps is
represented by Table~\ref{tbl:nt} ($a_0,a_1,a_2,a_3,a_4,$) is an
initial state of the RAM; first block consists of words $W_0,W_1,W_2$
and second block consists of $W_2,W_3,W_4$).

{\small
\begin{table}
\begin{center}
\caption{$RPXT_{2,1}$ test for $n=5$, $w=2$ based on 2-pseudo-exhaustive backgrounds $B_i^{
\label{tbl:nt}
\begin{tabular}{r|r|lllll||l} \hline\hline
$t$ & $r(W_j), w(W_j)$ & $W_0$  & $W_1$  & $W_2$ & $W_3$  & $W_4$ & $B_i$ \\  \hline\hline
$0$ &                        &  $a_0$      &  $a_1$   &    $a_2$    & $a_3$ & $a_4$ &  \\
$1$ & $w(W_0)$  &  ${\underline{0}}$ & $a_0$  & $a_1$ &  $a_2$ & $a_3$ &    \\
$2$ & $w(W_1)$  &  $0$ & ${\underline{0}}$  & $a_1$ &  $a_2$ & $a_3$ &    \\
$3$ & $w(W_2)$  &  $0$ & $0$  & ${\underline{0}}$ &  $a_2$ & $a_3$ &    \\
$4$ & $w(W_3)$  &  $0$ & $0$  & $0$ &  ${\underline{0}}$ & $a_3$ &    \\
$5$ & $w(W_4)$  &  $0$ & $0$  & $0$ &  $0$ & ${\underline{0}}$ & $B_0$  \\
\hline
$6$ & $r(W_2), w(W_2)$  & $0$ &  $0$ & ${\underline{1}}$ & $0$  & $0$ & \\
$7$ & $r(W_1), w(W_1)$  & $0$ &  ${\underline{1}}$ & $1$ & $0$  & $0$ & \\
$8$ & $r(W_0), w(W_0)$  & ${\underline{1}}$ &  $1$ & $1$ & $0$  & $0$ & $B_1$ \\ \hline
$9$ & $r(W_0), w(W_0)$ & ${\underline{1}}$ &  $1$ & $1$ & $0$ & $0$ & \\
$10$ & $r(W_1), w(W_1)$ & $1$ &  ${\underline{\alpha}}$ & $1$ & $0$ & $0$ &  \\
$11$ & $r(W_2), w(W_2)$ & $1$ &  $\alpha$ & ${\underline{\alpha^2}}$ & $0$ & $0$ &$B_2$  \\
$\ldots$ & $\ldots$ & $\ldots$ & $\ldots$ & $\ldots$ & $\ldots$ & $\ldots$ & $\ldots$ \\ \h
$48$ & $r(W_2), w(W_2)$ & $\alpha^2$ &  $\alpha$ & ${\underline{1}}$ & $0$ & $0$ & \\
$49$ & $r(W_1), w(W_1)$ & $\alpha^2$ &  ${\underline{\alpha}}$ & $1$ & $0$ & $0$ & \\
$50$ & $r(W_0), w(W_0)$ & ${\underline{0}}$ &  $\alpha$ & $1$ & $0$ & $0$ &  $B_{15}$ \\ \h
```

```
$51$ & $r(W_0), w(W_0)$ & ${\underline{1}}$ &  $\alpha$ & $1$ & $0$ & $0$ & \\
$52$ & $r(W_1), w(W_1)$ & $1$ &  ${\underline{1}}$ & $1$ & $0$ & $0$ & \\
$53$ & $r(W_2), w(W_2)$ & $1$ &  $1$ & ${\underline{1}}$ & $0$ & $0$ & $B_1$ \\ \hline
$54$ & $r(W_4), w(W_4)$  &  $1$ & $1$  & $1$ &  $0$ & ${\underline{1}}$ &   \\
$87$ & $r(W_3), w(W_3)$  &  $1$ & $1$  & $1$ &  ${\underline{1}}$ & $1$ &   \\
$88$ & $r(W_2), w(W_2)$  &  $1$ & $1$  & ${\underline{1}}$ &  $1$ & $1$ &   \\
$89$ & $r(W_1)$  &  $1$ & ${\underline{1}}$  & $1$ &  $1$ & $1$ &   \\
$90$ & $r(W_0)$  &  ${\underline{1}}$ & $1$  & $1$ &  $1$ & $1$ & $B_1$  \\ \hline
$90$ & $r(W_2), w(W_2)$ & $1$ &  $1$ & ${\underline{1}}$ &  $1$ & $1$ &  \\
$91$ & $r(W_3), w(W_3)$ & $1$ &  $1$ & $1$ &  ${\underline{\alpha}}$ & $1$ &   \\
$92$ & $r(W_4), w(W_4)$ & $1$ &  $1$ & $1$ &  $\alpha$ & ${\underline{\alpha^2}}$ & $B_2$
$\ldots$ & $\ldots$ & $\ldots$ & $\ldots$ & $\ldots$ & $\ldots$ & $\ldots$ & $\ldots$ \\ \h
$132$ & $r(W_4), w(W_4)$ & $1$ &  $1$ & $0$ &  $\alpha$ & ${\underline{1}}$ &  \\
$133$ & $r(W_3), w(W_3)$ & $1$ &  $1$ & $0$ &  ${\underline{1}}$ & $1$ &   \\
$134$ & $r(W_2), w(W_2)$ & $1$ &  $1$ & ${\underline{1}}$ &  $1$ & $1$ & $B_1$  \\ \hline
$135$ & $r(W_2)$ & $1$ &  $1$ & ${\underline{1}}$ &  $1$ & $1$ &  \\
$136$ & $r(W_3)$ & $1$ &  $1$ & $1$ &  ${\underline{1}}$ & $1$ &   \\
$137$ & $r(W_4)$ & $1$ &  $1$ & $1$ &  $1$ & ${\underline{1}}$ & $B_1$  \\ \hline
\end{tabular}
\end{center}
\end{table}
}

We have for complexity $L(RPXT_{k,k-1})$ of these tests

\begin{equation}
L(RPXT_{k,k-1})=2(q-1)(q^k) \lceil \frac{n}{q-1} \rceil +2n \approx  2^{wk+1}n+2n.
\label{eq:rc}
\end{equation}

Test complexities (in $sec$.) of $RPXT_{k,k-1}$ tests for different $k$ and $w=4$ are prese
$50nsec.$). For example, for a 4-bit memory with $N=nw=2^{18}$ bits detection of Static $SF


\begin{table}
\begin{center}
\caption{Time complexities (in seconds) for $RPXT_{k,k-1}$ tests for $(w=4)$, $k=2,3,4,5$ a
\label{tbl:n1c}
\begin{tabular}{c||c|c|c|c|c|c|c|c}
\multicolumn{9}{c}{~~~~~~~~~~~}\\ \hline \hline
  $N$  & $2^{8}$ & $2^{10}$  &  $2^{12}$  &  $2^{14}$  &  $2^{16}$ &  $2^{18}$ & $2^{20}$ &
 $k=2$  &  $0.00$  & $~0.00$ & $~~0.02$ & $~~0.10$ & $~~~0.41$ &  $~~~1.67$ &  $~~~6.71$ &
 $k=3$  &  $0.02$  & $~0.10$  & $~~0.41$ & $~~1.67$ & $~~~6.71$ & $~~26.84$ & $~107.37$ &
 $k=4$  &  $0.41$  & $~1.67$  & $~~6.71$ & $~26.84$ & $~107.37$ & $~429.49$ & $1717.98$ &
 $k=5$  & $6.71$ & $26.84$ & $107.37$ & $429.49$ & $1717.98$ &  $6871.04$ &  &
\end{tabular}
\end{center}
\end{table}



To summarise this section we note that as it follows from Table~\ref{tbl:n1c} tests $RPXT_{



\section{Conclusions}
\label{sec:sec6}

In this paper we have presented a unified approach for testing of
word-oriented memories based on the single  $PS(n,k)$ fault model
```

which covers SAFs, TFs, CFids, CFins, APSFs, PPSFs and SPSFs.
A systematic approach for generating data backgrounds $B(n,k,w)$
has been proposed, based on $Reed-Solomon$ codes over
$GF(2^w)$, where w is the number bits per word. Combining
k-pseudo-exhaustive backgrounds $B(n,k,w)$ with the $MATS+$ test
algorithm we presented a range of optimal pseudo-exhaustive tests.

For the case when faults are restricted to a neighbourhood consisting
of at most $2^{w-1}-1$ words we propose the test $RPXT_{k,k-1}$. Test
$RPXT_{k,k-1}$, with complexity $2^{kw+1}n + 2n$, verifies for any k
words all 2^{kw} states of the words and all 2^{2w} transitions
within one word for any fixed state of any other $k-2$ words for the
memory-under-test block with the size $\lceil (q-1)/2 \rceil -1$.

The deterministic 100\% fault coverage, also for the complex PSFs
involving a large number of words, causes it to be preferred above
pseudo-random tests in many applications, while due to its systematic
nature it renders itself well for BIST applications.

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