US008634240B2

(12) **United States Patent**
Gavens et al.

(10) **Patent No.: US 8,634,240 B2**
(45) **Date of Patent: Jan. 21, 2014**

(54) **NON-VOLATILE MEMORY AND METHOD WITH ACCELERATED POST-WRITE READ TO MANAGE ERRORS**

(75) Inventors: **Lee M. Gavens**, Milpitas, CA (US); **Jian Chen**, Menlo Park, CA (US)

(73) Assignee: **Sandisk Technologies, Inc.**, Plano, TX (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 138 days.

(21) Appl. No.: **12/874,064**

(22) Filed: **Sep. 1, 2010**

(65) **Prior Publication Data**

US 2011/0096601 A1 Apr. 28, 2011

Related U.S. Application Data

(63) Continuation-in-part of application No. 12/642,728, filed on Dec. 18, 2009, now Pat. No. 8,423,866, which is a continuation-in-part of application No. 12/607,522, filed on Oct. 28, 2009, now Pat. No. 8,214,700.

(51) **Int. Cl.**
G11C 16/06 (2006.01)

(52) **U.S. Cl.**
USPC **365/185.09**; 365/185.03; 365/185.04; 365/185.05; 365/185.11; 365/185.12; 365/185.17; 365/185.21; 365/185.22; 365/200; 365/230.03

(58) **Field of Classification Search**
USPC 365/185.03, 185.04, 185.05, 185.09, 365/185.11, 185.12, 185.17, 185.21, 365/185.22, 200, 230.03
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,070,032	A	12/1991	Yuan et al.
5,095,344	A	3/1992	Harari
5,313,421	A	5/1994	Guterman et al.
5,315,541	A	5/1994	Harari et al.
5,321,699	A	6/1994	Endoh et al.
5,343,063	A	8/1994	Yuan et al.
5,386,422	A	1/1995	Endoh et al.
5,469,444	A	11/1995	Endoh et al.

(Continued)

FOREIGN PATENT DOCUMENTS

EP 709782 A2 5/1996

OTHER PUBLICATIONS

Notice of Allowance and Fees Due for U.S. Appl. No. 12/607,522 mailed Mar. 2, 2012, 17 pages.

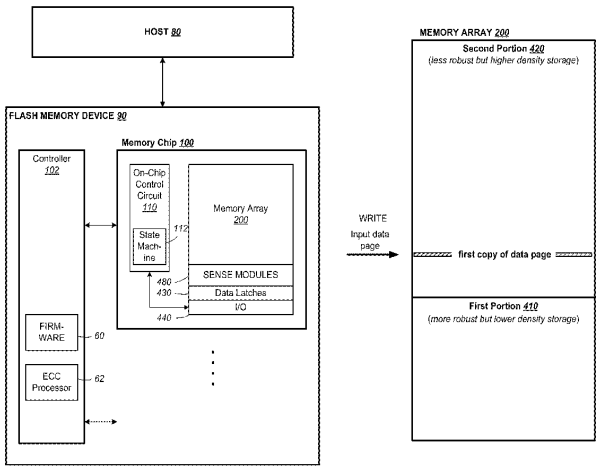
(Continued)

Primary Examiner — Fernando Hidalgo
(74) *Attorney, Agent, or Firm* — Davis Wright Tremaine LLP

(57) **ABSTRACT**

Data errors in non-volatile memory inevitably increase with usage and with higher density of bits stored per cell. The memory is configured to have a first portion operating with less error but of lower density storage, and a second portion operating with a higher density but less robust storage. An error management provides reading and checking the copy after copying to the second portion. If the copy has excessive error bits, it is repeated in a different location either in the second or first portion. The reading and checking of the copy is accelerated by reading only a sample of it. The sample is selected from a subset of the copy having its own ECC and estimated to represent a worst error rate among the copy it is sampling. One embodiment has the sample taken from one bit of each multi-bit memory cell of a group.

18 Claims, 31 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

5,570,315	A	10/1996	Tanaka et al.	
5,595,924	A	1/1997	Yuan et al.	
5,602,789	A	2/1997	Endoh et al.	
5,661,053	A	8/1997	Yuan	
5,671,388	A	9/1997	Hasbun et al.	
5,768,192	A	6/1998	Eitan	
5,859,795	A	1/1999	Rolandi	
5,867,429	A	2/1999	Chen et al.	
5,903,495	A	5/1999	Takeuchi et al.	
5,930,167	A *	7/1999	Lee et al.	365/185.03
6,011,287	A	1/2000	Itoh et al.	
6,011,725	A	1/2000	Eitan	
6,046,935	A	4/2000	Takeuchi et al.	
6,064,591	A	5/2000	Takeuchi et al.	
6,134,140	A	10/2000	Tanaka et al.	
6,141,388	A *	10/2000	Servais et al.	375/262
6,222,762	B1	4/2001	Guterman et al.	
6,456,528	B1	9/2002	Chen	
6,625,061	B2	9/2003	Higuchi	
6,914,823	B2	7/2005	Chen et al.	
6,917,542	B2	7/2005	Chen et al.	
6,917,543	B2	7/2005	Sato	
7,009,889	B2	3/2006	Tran et al.	
7,177,184	B2	2/2007	Chen	
7,376,011	B2	5/2008	Conley et al.	
7,428,180	B2	9/2008	Kim	
7,554,842	B2	6/2009	Barzilai et al.	
7,864,578	B2	1/2011	Takada	
8,094,500	B2	1/2012	Paley et al.	
8,214,700	B2	7/2012	Chen	
2004/0109357	A1 *	6/2004	Cernea et al.	365/185.21
2005/0068802	A1	3/2005	Tanaka	
2007/0201274	A1	8/2007	Yu et al.	
2007/0234183	A1	10/2007	Hwang et al.	
2007/0263469	A1 *	11/2007	Cornwell et al.	365/226
2008/0112238	A1	5/2008	Kim et al.	
2008/0177956	A1	7/2008	Peddle	
2008/0301532	A1	12/2008	Uchikawa et al.	
2009/0073763	A1	3/2009	Hosono	
2009/0190397	A1	7/2009	Cho et al.	
2009/0327591	A1	12/2009	Moshayedi	
2010/0074024	A1 *	3/2010	Roohparvar	365/185.19
2010/0131809	A1	5/2010	Katz	
2010/0172180	A1	7/2010	Paley et al.	
2011/0035538	A1	2/2011	Kim et al.	
2011/0096601	A1	4/2011	Gavens et al.	
2011/0099418	A1	4/2011	Chen	
2011/0099460	A1	4/2011	Dusija et al.	
2011/0149651	A1	6/2011	Gorobets	
2011/0153912	A1	6/2011	Gorobets et al.	
2011/0161784	A1	6/2011	Selinger et al.	
2011/0173378	A1	7/2011	Filor et al.	
2012/0311244	A1	12/2012	Huang	

OTHER PUBLICATIONS

Office Action for U.S. Appl. No. 12/642,728 mailed May 7, 2012, 15 pages.

Eitan et al., "NROM: A Novel Localized Trapping, 2-Bit Nonvolatile Memory Cell," IEEE Electron Device Letters, vol. 21, No. 11, Nov. 2000, pp. 543-545.

Communication Relating to the Results of the Partial International Search, International Application No. PCT/US2012/048074, mailed Nov. 29, 2012, 7 pages.

Notice of Allowance and Fees Due for U.S. Appl. No. 13/540,279, mailed Oct. 16, 2012, 10 pages.

International Search Report and Written Opinion for Application No. PCT/US2012/048087 dated Feb. 18, 2013, 19 pages.

International Search Report and Written Opinion for Application No. PCT/US2012/048074 dated Feb. 26, 2013, 18 pages.

Notification of Transmittal of the International Search Report and the Written Opinion of the International Searching Authority, or the Declaration for Int'l Appl No. PCT/US2012/048074 mailed Feb. 26, 2013, 18 pages.

Notification of Transmittal of the International Search Report and the Written Opinion of the International Searching Authority, or the Declaration for Int'l Appl No. PCT/US2012/048087 mailed Feb. 18, 2013, 19 pages.

Office Action for U.S. Appl. No. 12/642,728 mailed Sep. 17, 2012, 10 pages.

Notice of Allowance for U.S. Appl. No. 12/642,728 mailed Dec. 5, 2012, 10 pages.

EPO/ISA, "Notification of Transmittal of the International Search Report and the Written Opinion of the International Searching Authority, or the Declaration," corresponding International Patent Application No. PCT/US2010/053792, mailed on Feb. 4, 2011, 11 pages.

EPO/ISA, "Notification of Transmittal of the International Search Report and the Written Opinion of the International Searching Authority, or the Declaration," corresponding International Patent Application No. PCT/US2010/053805, mailed on Feb. 4, 2011, 10 pages.

EPO/ISA, "Notification of Transmittal of the International Search Report and the Written Opinion of the International Searching Authority, or the Declaration," corresponding International Patent Application No. PCT/US2010/053813, mailed on Feb. 9, 2011, 10 pages.

* cited by examiner

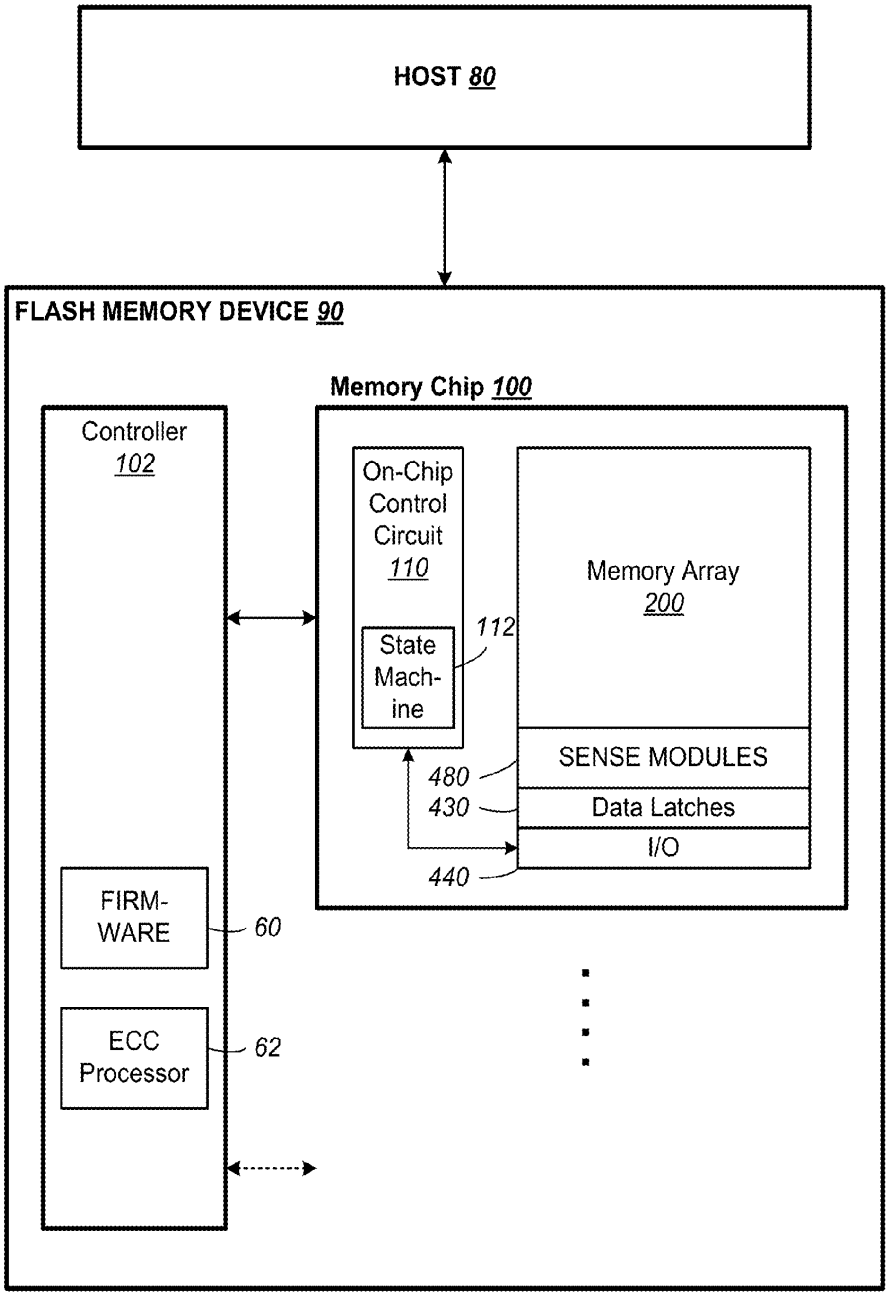

HOST 80
FLASH MEMORY DEVICE 90
Memory Chip 100
Controller 102
On-Chip Control Circuit 110
State Mach-ine
112
Memory Array 200
SENSE MODULES
480
430
Data Latches
I/O
440
FIRM-WARE
60
ECC Processor
62

FIG. 1

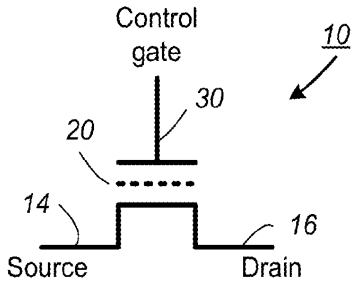

Control
gate
10
30
20
14
16
Source
Drain

FIG. 2

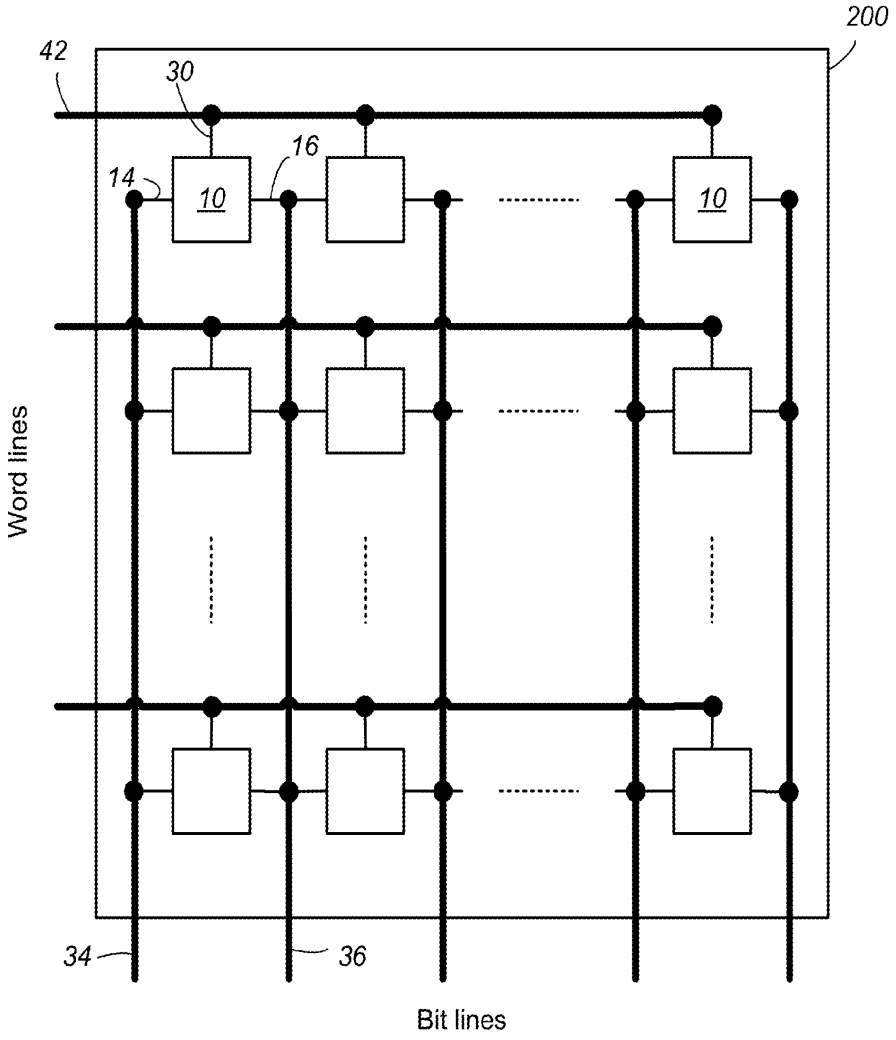

200
42
30
16
14
10
10
Word lines
34
36
Bit lines

FIG. 3

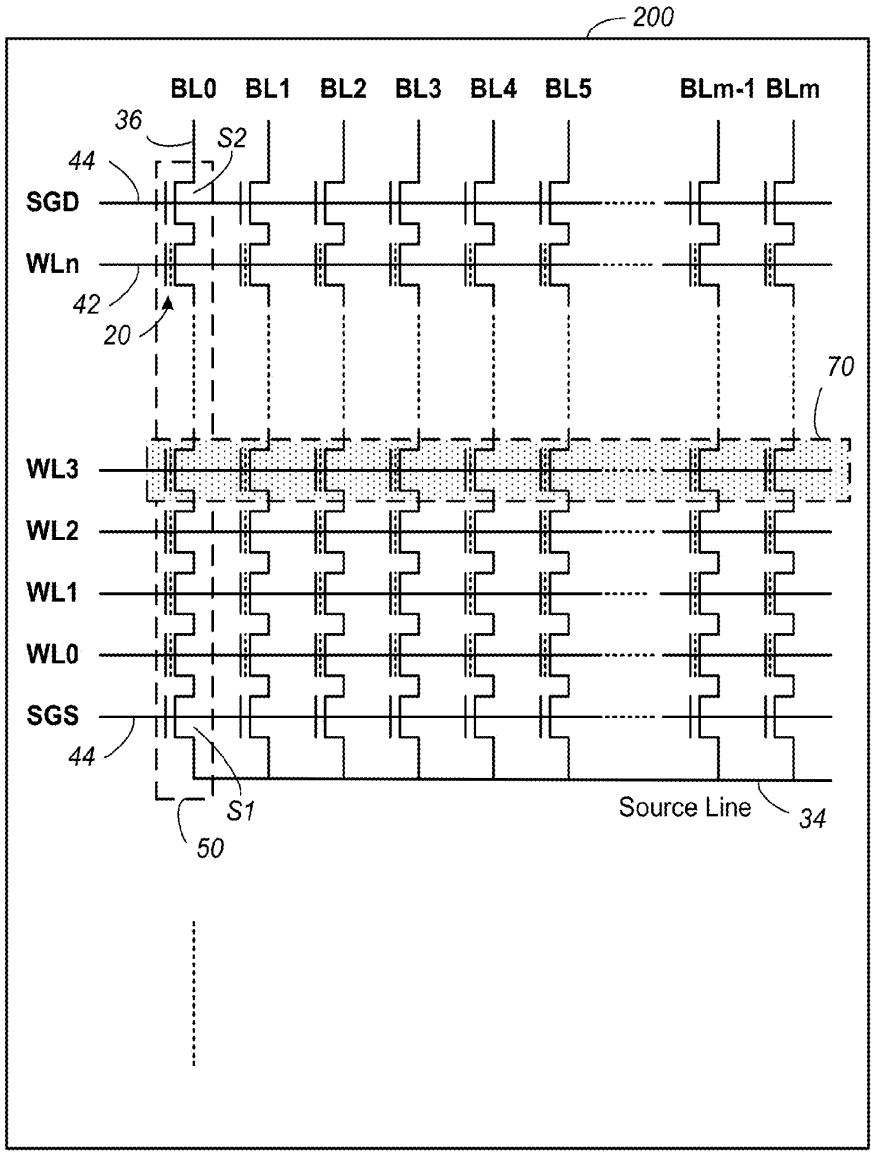

200
BL0
BL1
BL2
BL3
BL4
BL5
BLm-1
BLm
36
S2
44
SGD
WLn
42
20
70
WL3
WL2
WL1
WL0
SGS
44
S1
50
Source Line
34

FIG. 4

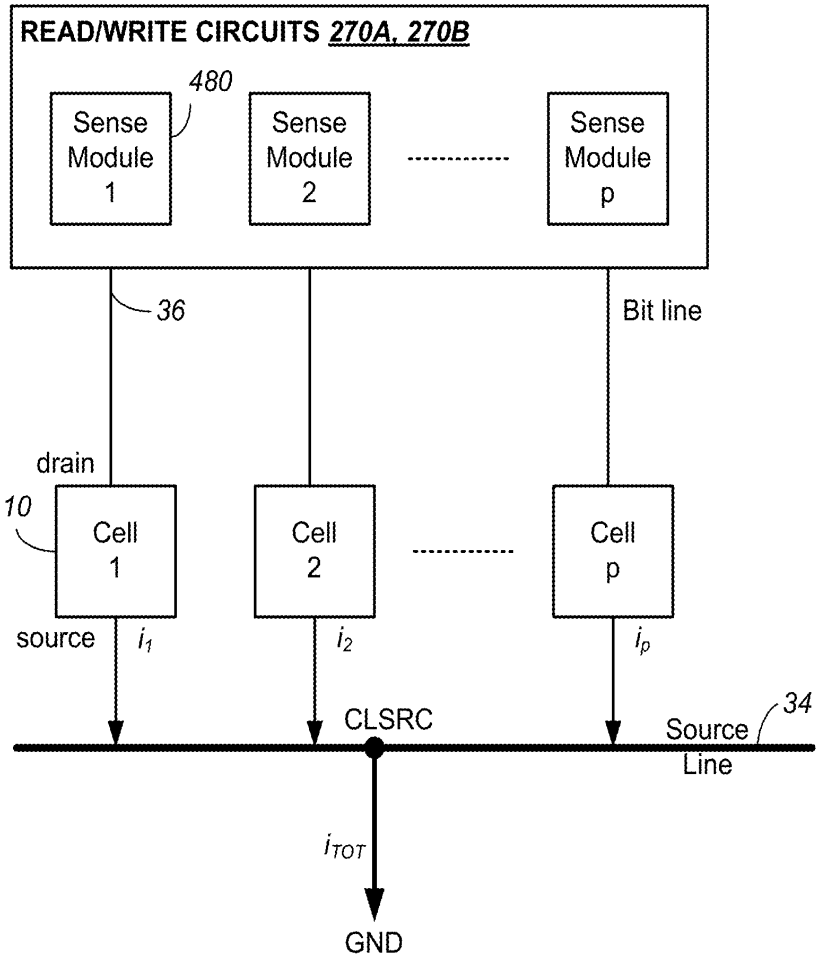

READ/WRITE CIRCUITS 270A, 270B
480
Sense Module 1
Sense Module 2
Sense Module p
36
Bit line
drain
10
Cell 1
Cell 2
Cell p
source
i_1
i_2
i_p
CLSRC
34
Source Line
i_{TOT}
GND

FIG. 5A

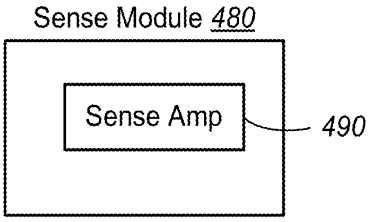

Sense Module 480
Sense Amp
490

FIG. 5B

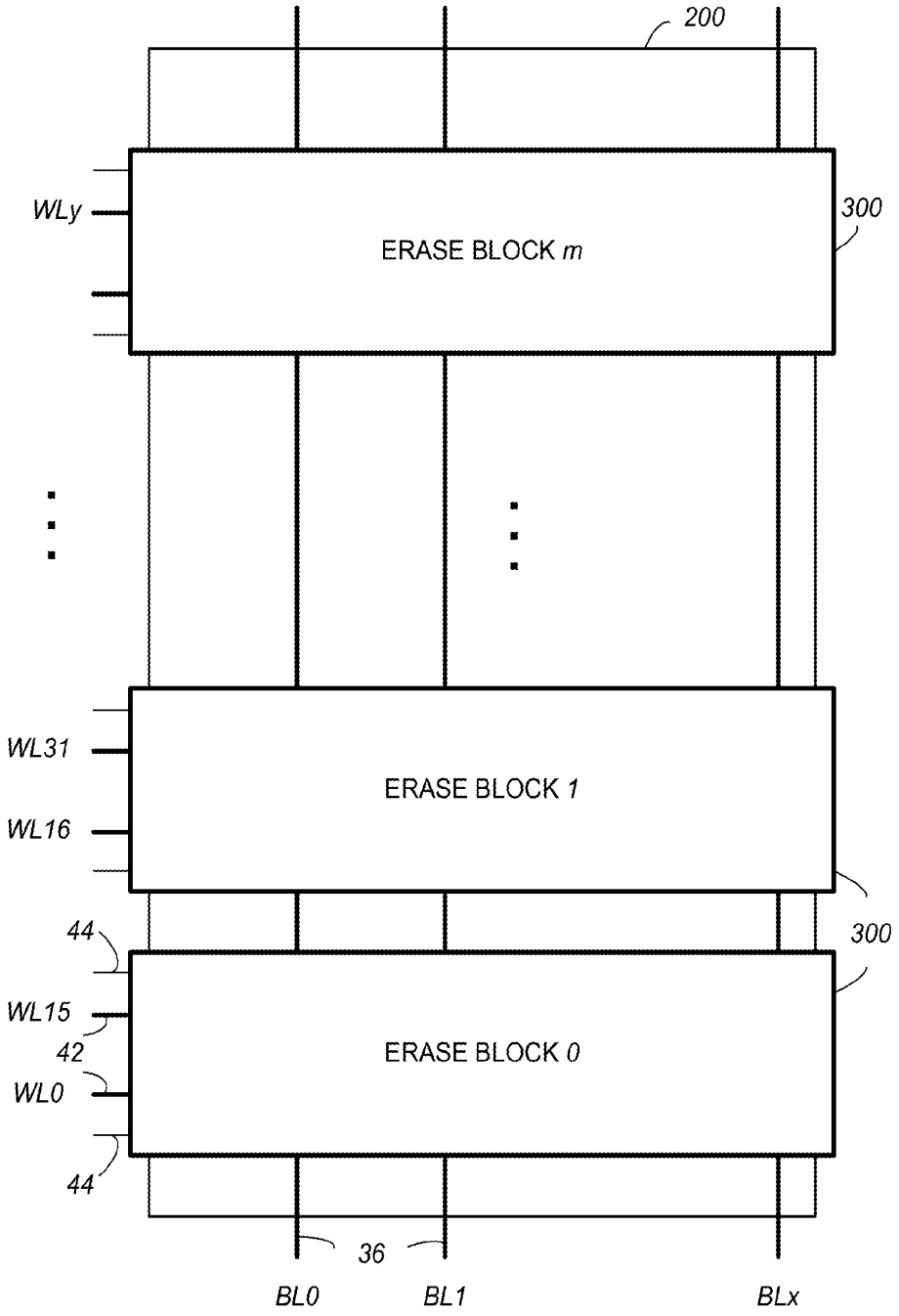
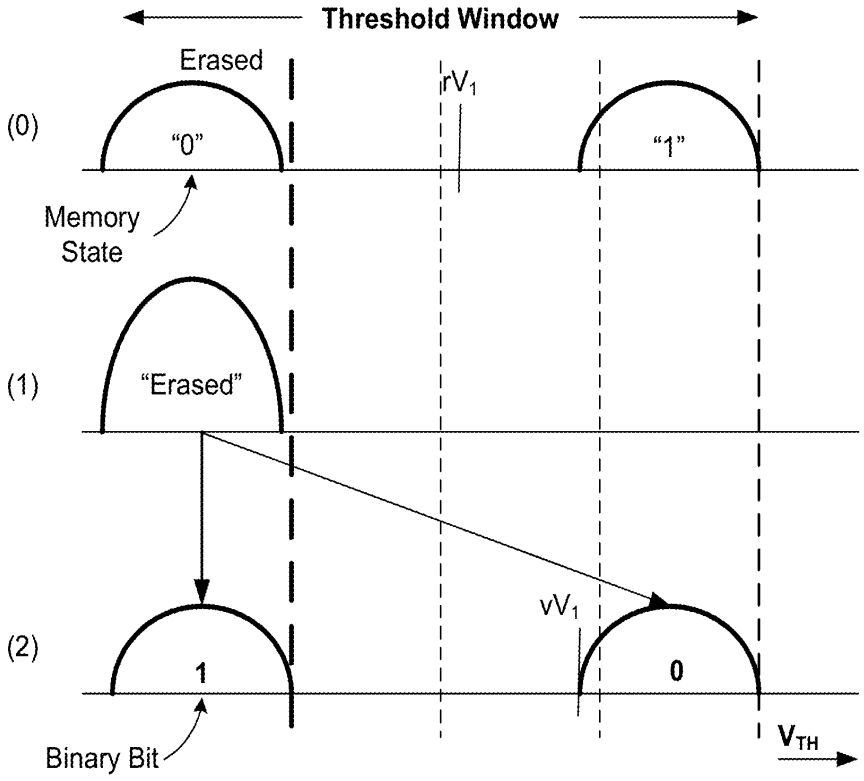
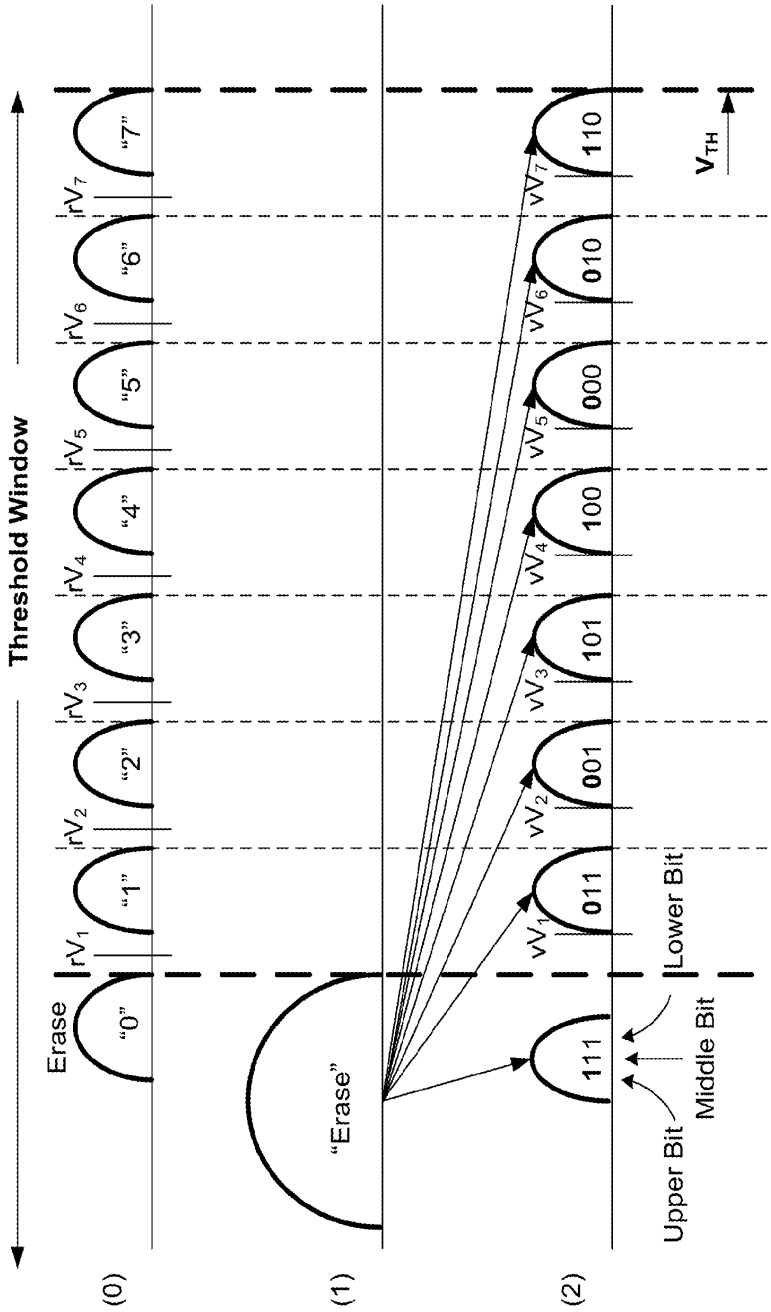

200
WLy
ERASE BLOCK m
300
WL31
ERASE BLOCK 1
WL16
44
300
WL15
42
ERASE BLOCK 0
WL0
44
36
BL0
BL1
BLx

FIG. 6



Programming into two states represented by a 1-bit code

FIG. 7



Programming into four states represented by a 3-bit code

FIG. 8

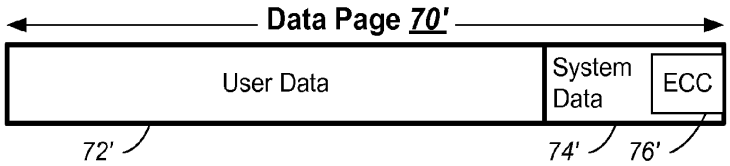


FIG. 9

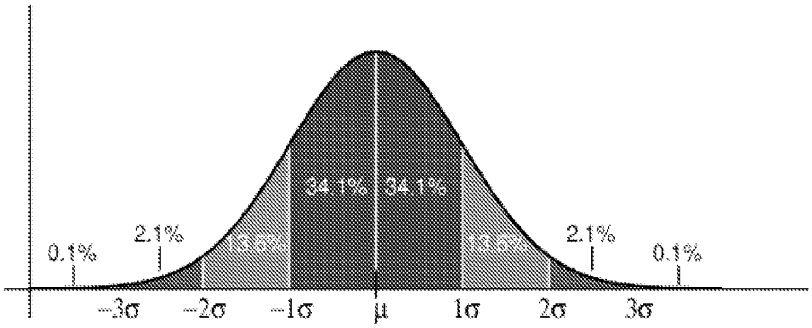


FIG. 10A

Sigma Value	Cumulative value	Cumulative %	Example Error Rate at EOL
1σ	1.59E-01	15.86500000%	...
1.645σ	5.00E-02	5.00000000%	1 bits
1.960σ	2.50E-02	2.50000000%	...
2σ	2.28E-02	2.27500000%	2 bits
2.576σ	5.00E-03	0.50000000%	...
3σ	1.35E-03	0.13500000%	4 bits
3.2906σ	5.00E-04	0.05000000%	...
4σ	3.17E-05	0.00316700%	8 bits
5σ	2.87E-07	0.00028670%	30 bits
6σ	9.86E-10	0.00000010%	42 bits
7σ	1.28E-12	0.00000000%	...

FIG. 10B

	ERROR SOURCE	DESCRIPTION
(A)	$E_{PW}(N_{CYC})$	Bit errors that are present soon after the page is written. They increase with N_{CYC}, the number of program-erase cycling, which is a measure of the endurance of a block.
(B)	$E_{DR}(T, N_{CYC})$	Bit errors due to data retention at EOL ("end of life") T = Temperature
(C)	$E_{RD}(N_R, N_{CYC})$	Bit errors due to read disturb which increase with the number of reads N_R and endurance

FIG. 11

(A)	$E_{TOT}(N_{CYC}, N_R)$	$= E_{PW}(N_{CYC}) + E_{DR}(T, N_{CYC}) + E_{RD}(N_R, N_{CYC})$
(B)	*(fresh after 1 year)* $E_{TOT}(1, 1M)$	$E_{PW}(N_{CYC}) + E_{DR}(85°C, 1) + E_{RD}(1M, 1)$ **= 3 + 2 + 0 = 5 bits**
(C)	*(memory at EOL)* $E_{TOT}(10K, 1M)$	$E_{PW}(10K) \sim 10$, $E_{DR}(85°C, 10K) \sim 10$, and $E_{RD}(1M, 10K) \sim 1$ = 10+10+1 **= 21 bits**

Examples of Total Errors at the beginning and end of life

FIG. 12

ECC_{DESIGN}	Must be designed to correct for worst case E_{TOT}(after EOL cycling, Data Retention specification)

FIG. 13

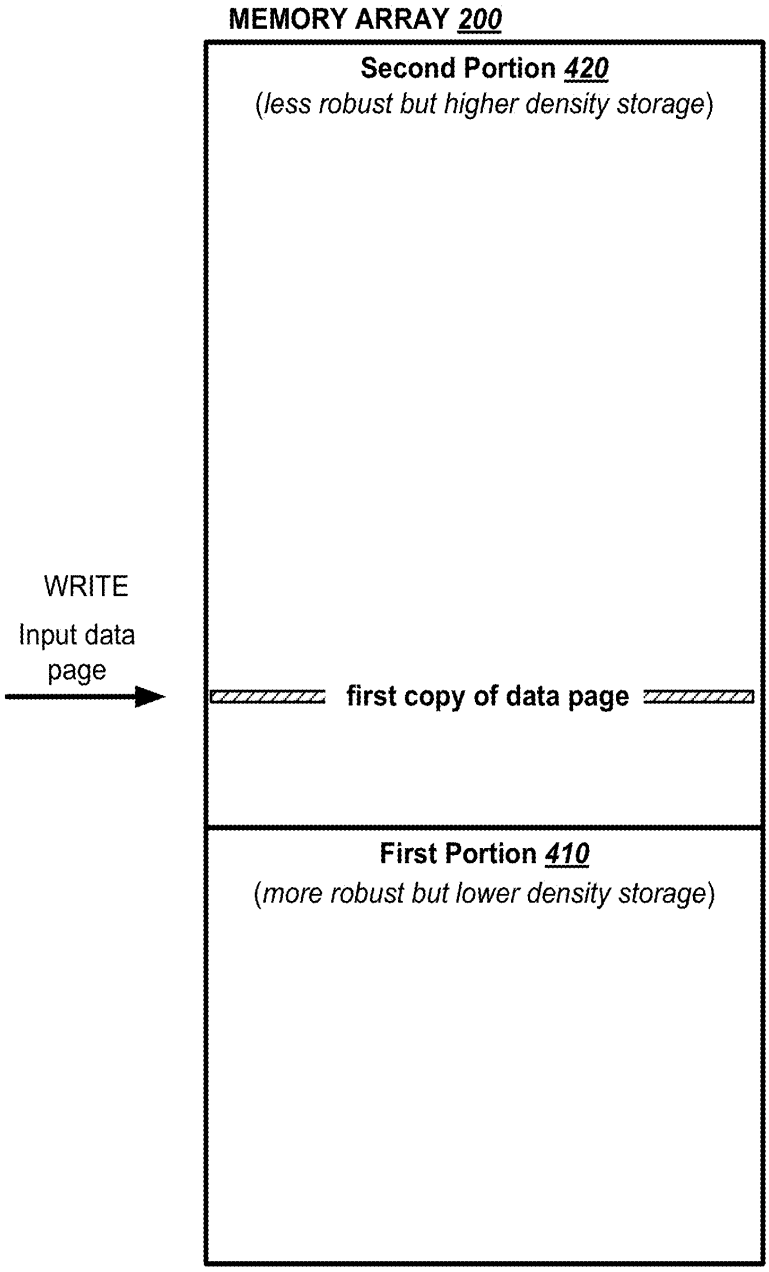

MEMORY ARRAY 200
Second Portion 420
(less robust but higher density storage)
WRITE
Input data page
first copy of data page
First Portion 410
(more robust but lower density storage)

FIG. 14A

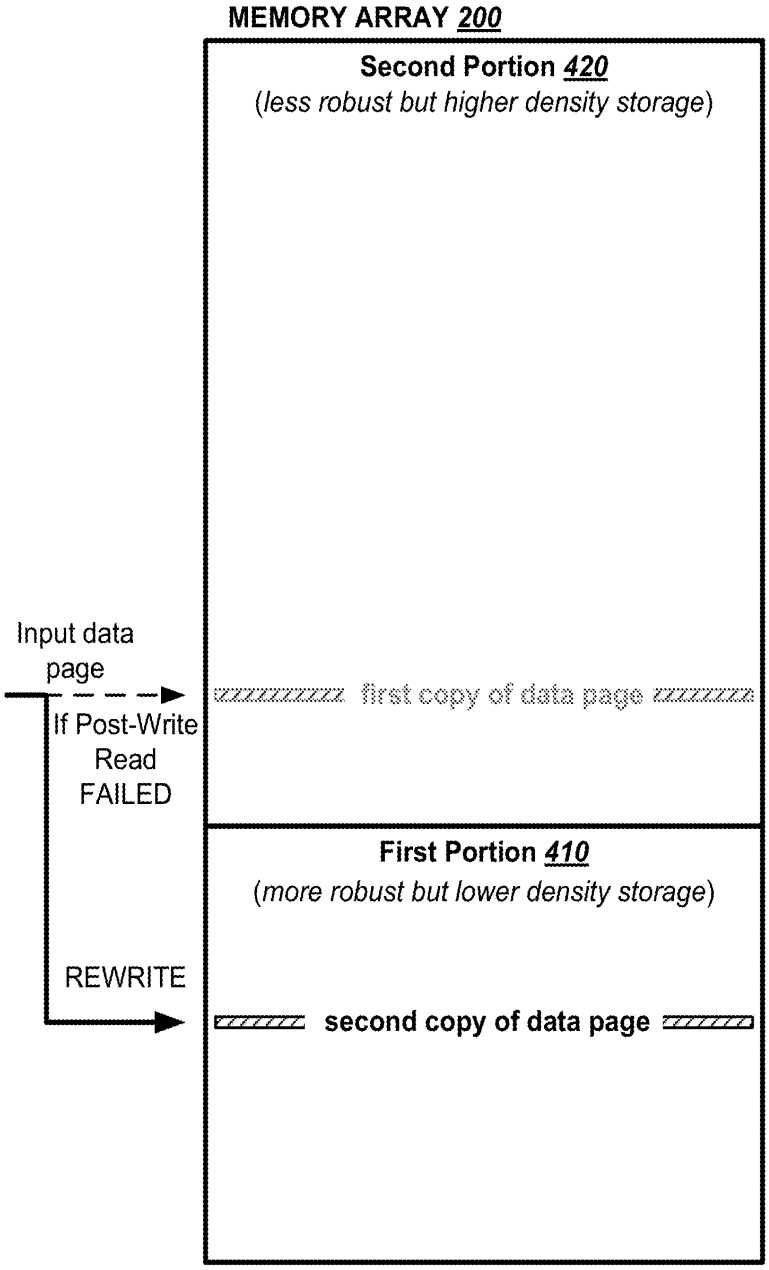

MEMORY ARRAY 200
Second Portion 420
(less robust but higher density storage)
Input data page
first copy of data page
If Post-Write Read FAILED
First Portion 410
(more robust but lower density storage)
REWRITE
second copy of data page

FIG. 14B

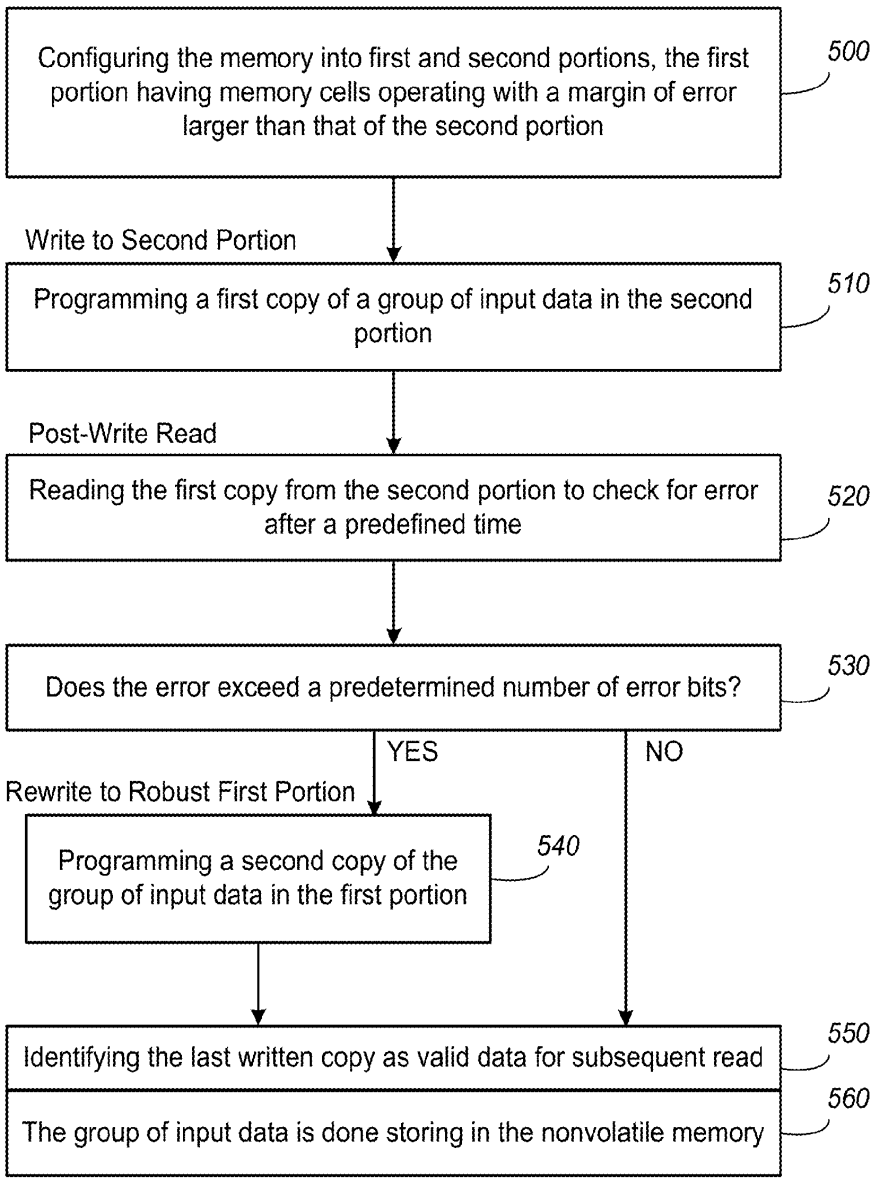

Configuring the memory into first and second portions, the first portion having memory cells operating with a margin of error larger than that of the second portion
500
Write to Second Portion
Programming a first copy of a group of input data in the second portion
510
Post-Write Read
Reading the first copy from the second portion to check for error after a predefined time
520
Does the error exceed a predetermined number of error bits?
530
YES
NO
Rewrite to Robust First Portion
Programming a second copy of the group of input data in the first portion
540
Identifying the last written copy as valid data for subsequent read
550
The group of input data is done storing in the nonvolatile memory
560

FIG. 15

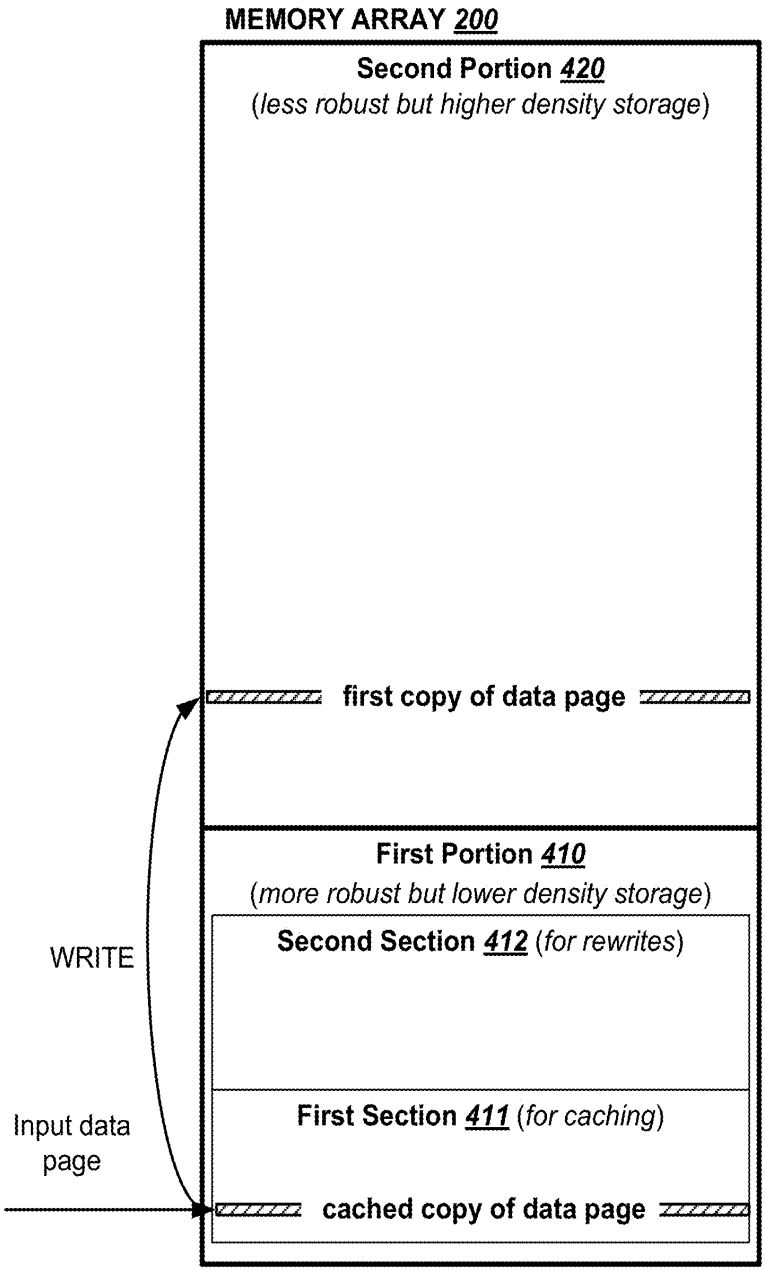

MEMORY ARRAY 200
Second Portion 420
(less robust but higher density storage)
first copy of data page
First Portion 410
(more robust but lower density storage)
Second Section 412 (for rewrites)
First Section 411 (for caching)
cached copy of data page
WRITE
Input data page

FIG. 16A

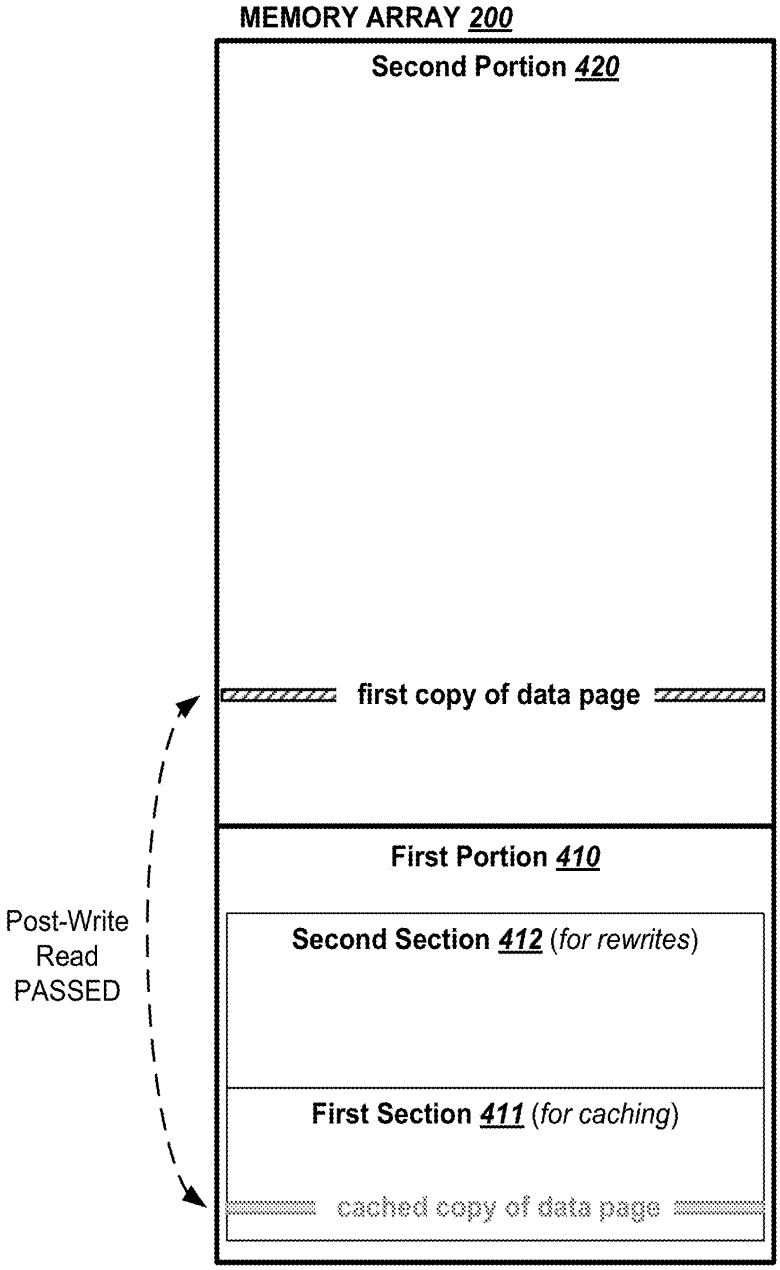

MEMORY ARRAY 200
Second Portion 420
first copy of data page
First Portion 410
Post-Write Read PASSED
Second Section 412 (for rewrites)
First Section 411 (for caching)
cached copy of data page

FIG. 16B

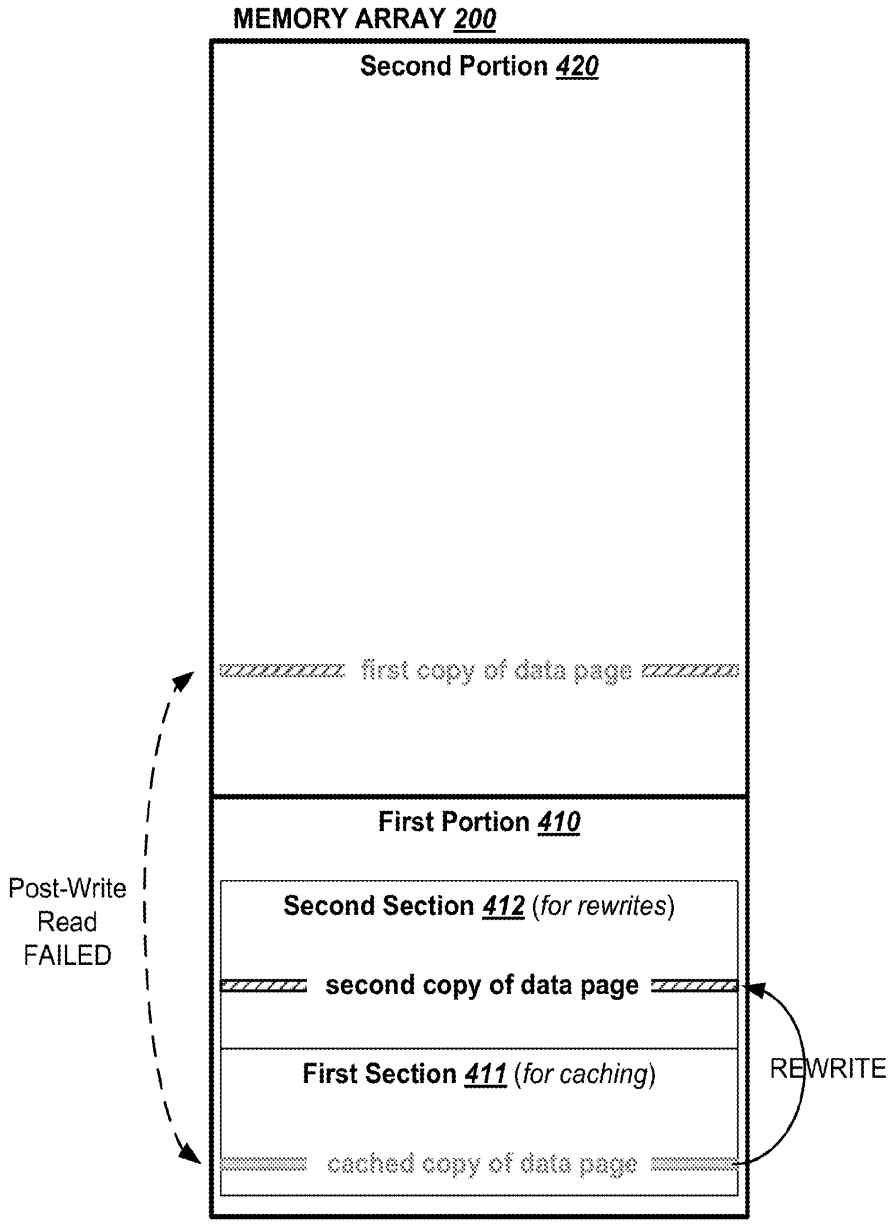

MEMORY ARRAY 200
Second Portion 420
first copy of data page
First Portion 410
Post-Write
Read
FAILED
Second Section 412 (for rewrites)
second copy of data page
First Section 411 (for caching)
REWRITE
cached copy of data page

FIG. 16C

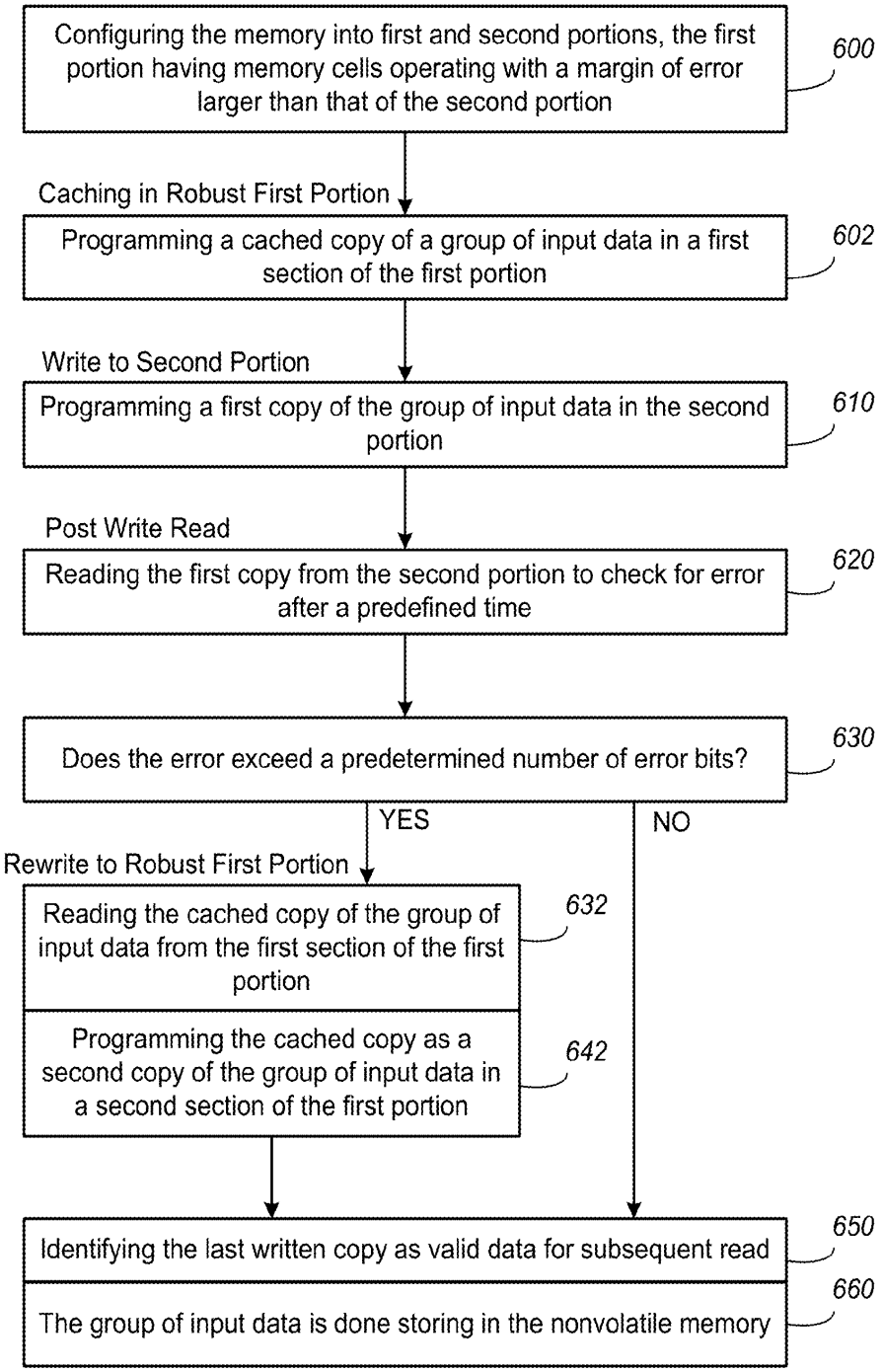

Configuring the memory into first and second portions, the first portion having memory cells operating with a margin of error larger than that of the second portion
600
Caching in Robust First Portion
Programming a cached copy of a group of input data in a first section of the first portion
602
Write to Second Portion
Programming a first copy of the group of input data in the second portion
610
Post Write Read
Reading the first copy from the second portion to check for error after a predefined time
620
Does the error exceed a predetermined number of error bits?
630
YES
NO
Rewrite to Robust First Portion
Reading the cached copy of the group of input data from the first section of the first portion
632
Programming the cached copy as a second copy of the group of input data in a second section of the first portion
642
Identifying the last written copy as valid data for subsequent read
650
The group of input data is done storing in the nonvolatile memory
660

FIG. 17

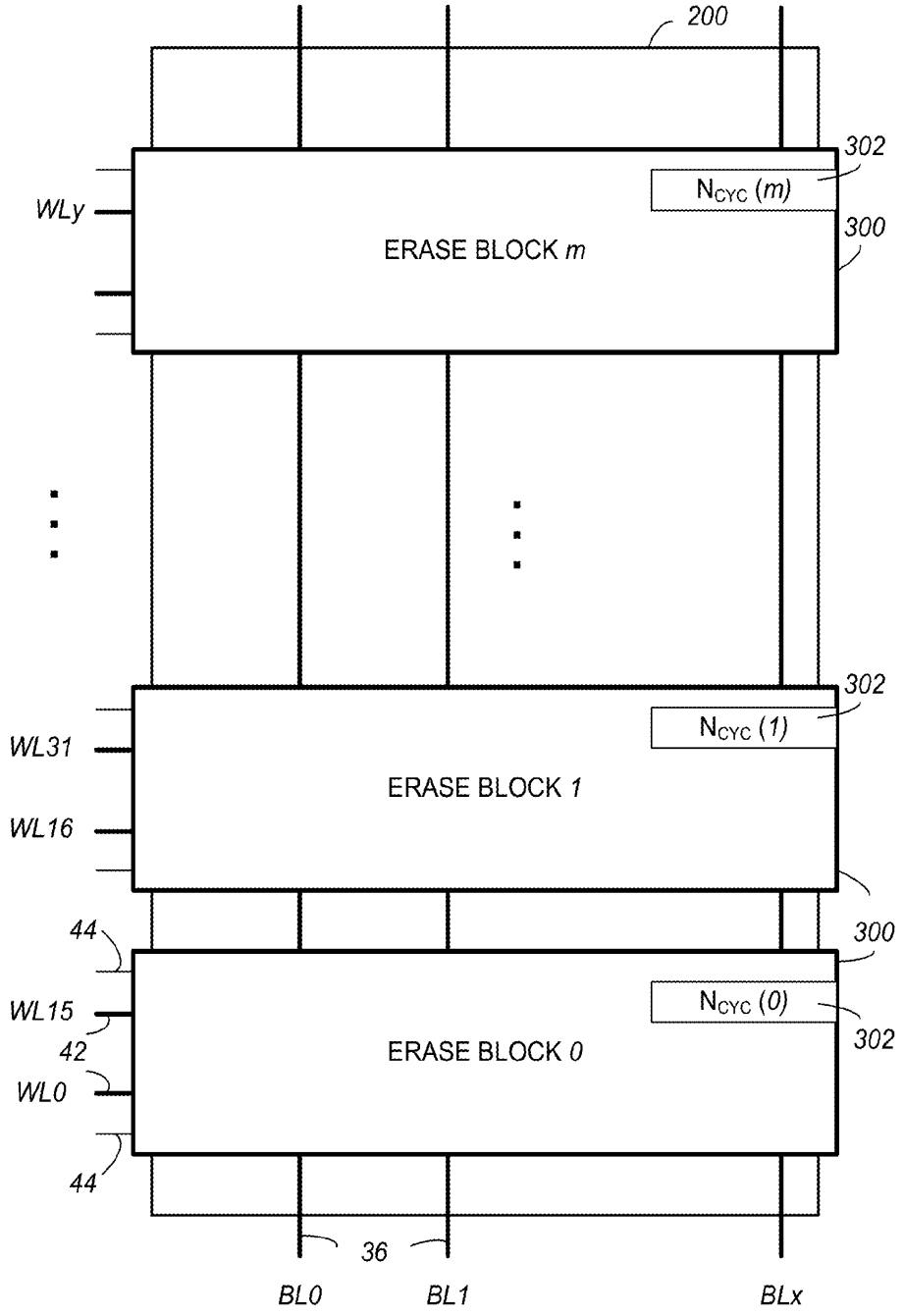

200
302
N_{CYC} (m)
WLy
300
ERASE BLOCK m
302
N_{CYC} (1)
WL31
ERASE BLOCK 1
WL16
44
300
N_{CYC} (0)
WL15
302
42
ERASE BLOCK 0
WL0
44
36
BL0
BL1
BLx

FIG. 18

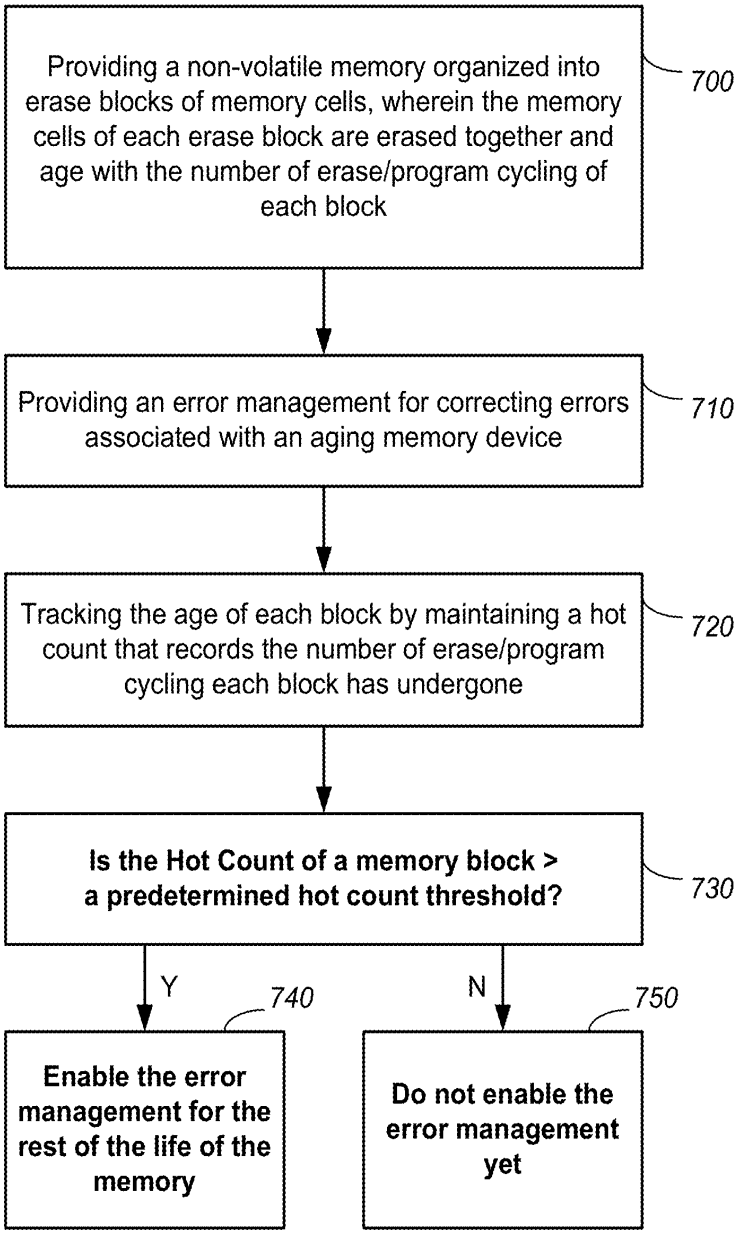
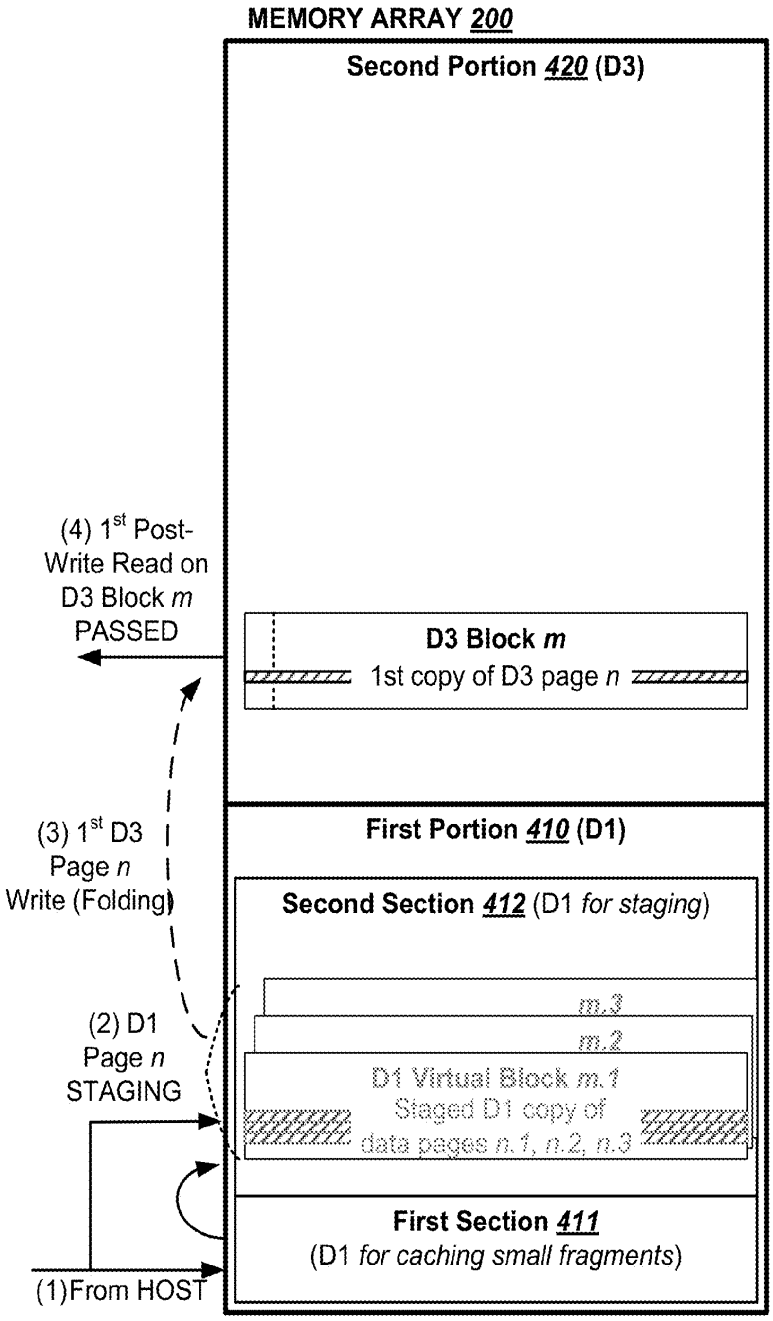
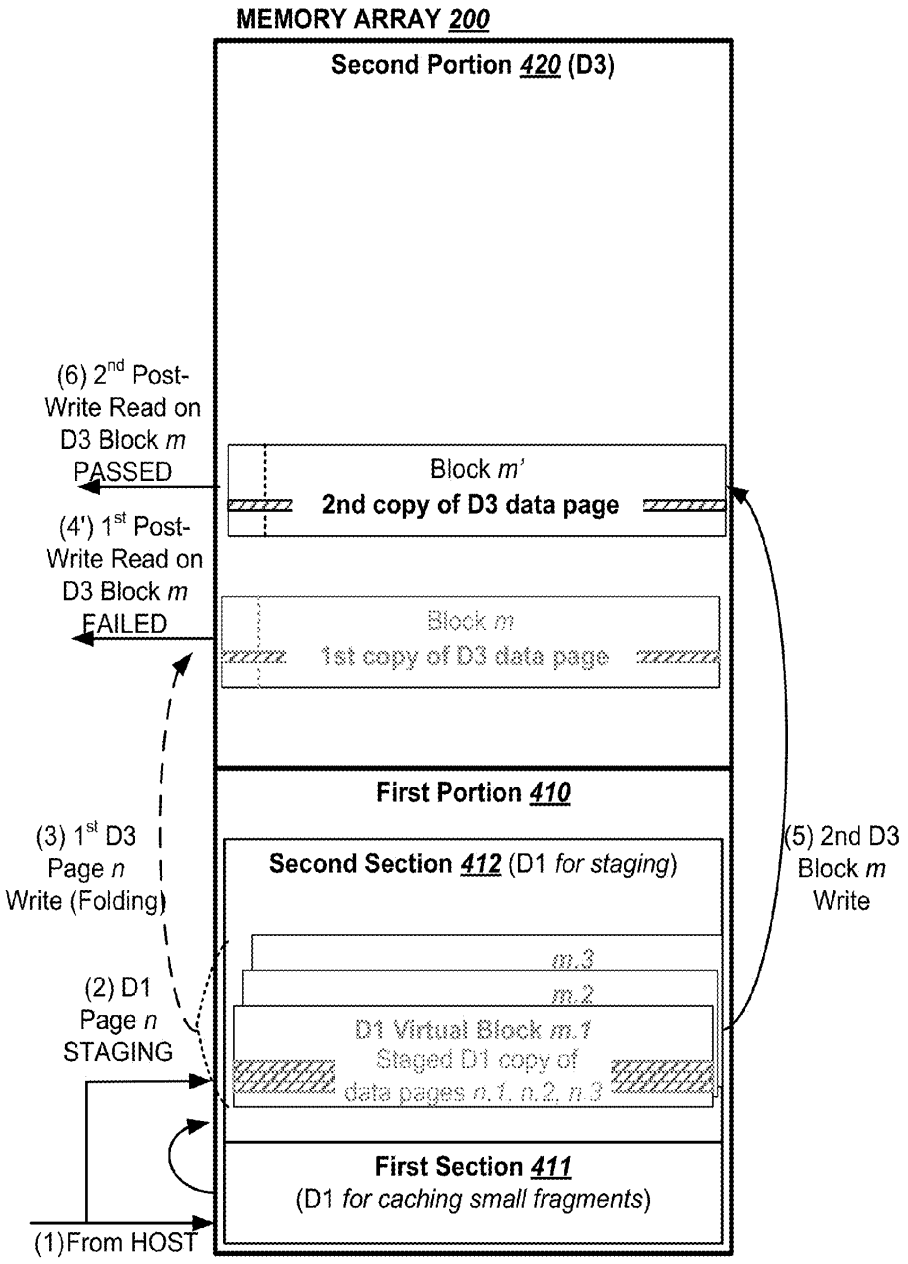

Providing a non-volatile memory organized into erase blocks of memory cells, wherein the memory cells of each erase block are erased together and age with the number of erase/program cycling of each block
700
Providing an error management for correcting errors associated with an aging memory device
710
Tracking the age of each block by maintaining a hot count that records the number of erase/program cycling each block has undergone
720
Is the Hot Count of a memory block > a predetermined hot count threshold?
730
Y
N
740
750
Enable the error management for the rest of the life of the memory
Do not enable the error management yet

FIG. 19



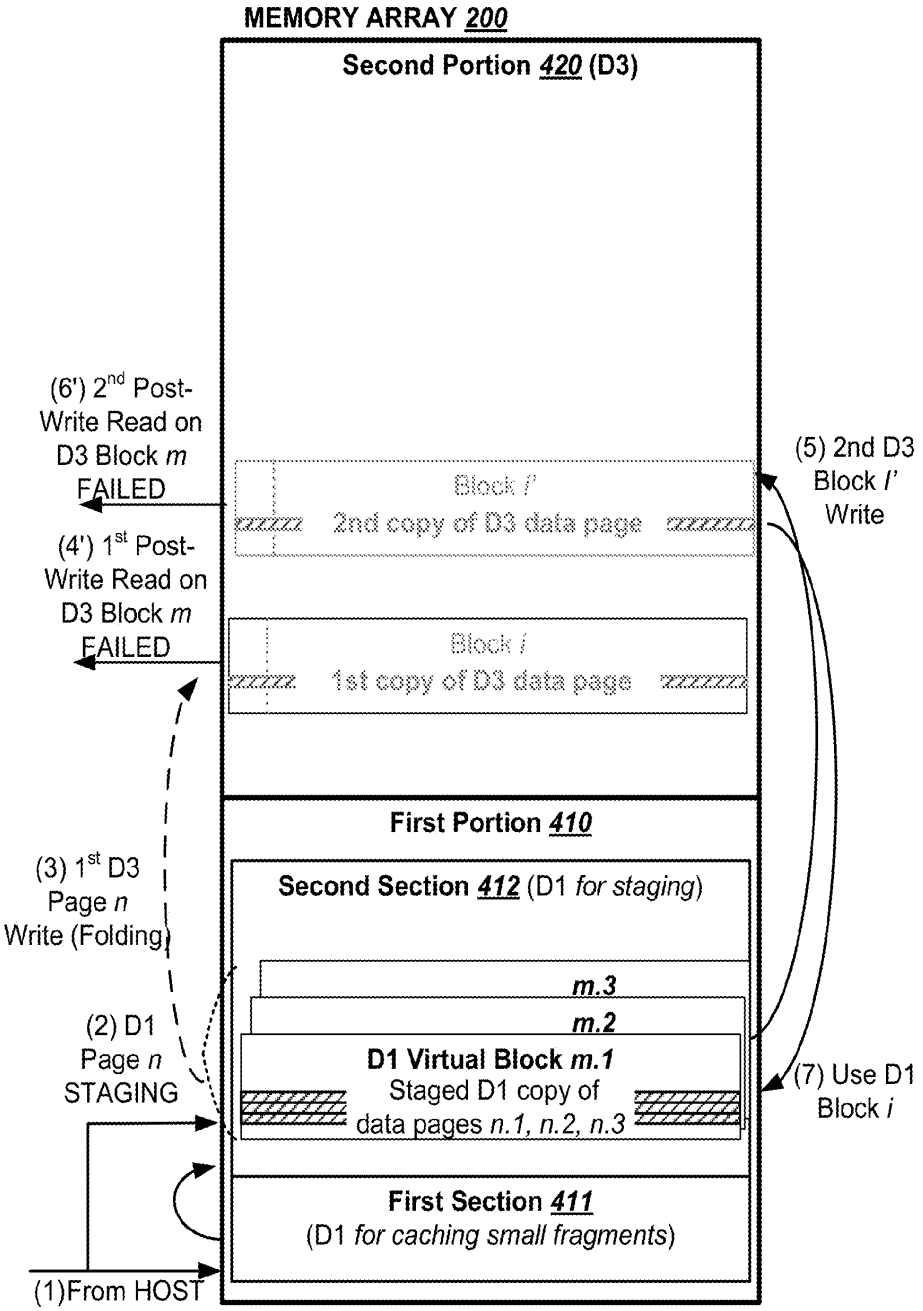
Example of successful D1 to D3 Folding

FIG. 20A



Example of Read Error after 1st D1 to D3 Folding

FIG. 20B



Example of Read Error after 2nd D1 to D3 Folding

FIG. 20C

File System Configuration File

PARAMETER	DESCRIPTION
E_pw_check	a variable set in File System Configuration File to specify at what # of ECC bits level, a D3 block is consider high risk and restart of D1 to D3 folding to a new D3 block is required
ECC_threshold_ SLC	a variable is needed in File System Configuration File for maintaining SLC threshold to compare against in order to make a decision to continue with EPWR or not
EPWR_enable_ flag	controlled in File System Configuration File. 0 = not set (Default); 1 = set when EPWR is enabled
Hot_count_ enable_flag	0 = not enabled; 1 = enabled
Hot_count_ threshold_EPWR	a variable set in File System Configuration File to specify at what hot count level, EPWR is needed. If hot count of all D3 blocks is < hot count threshold, even EPWR enable flag is on, EPWR process is not triggered
EPWR_verify_ page_budget	a variable set in File System Configuration File to specify how many pages can be read during 1 phase of EPWR
EPWR_retries	a variable in File System Configuration File to limit number of retry attempts
D3_Block_max _retries	a variable in File System Configuration File to limit the total number of retry attempts on a D3 block over lifetime

FIG. 21

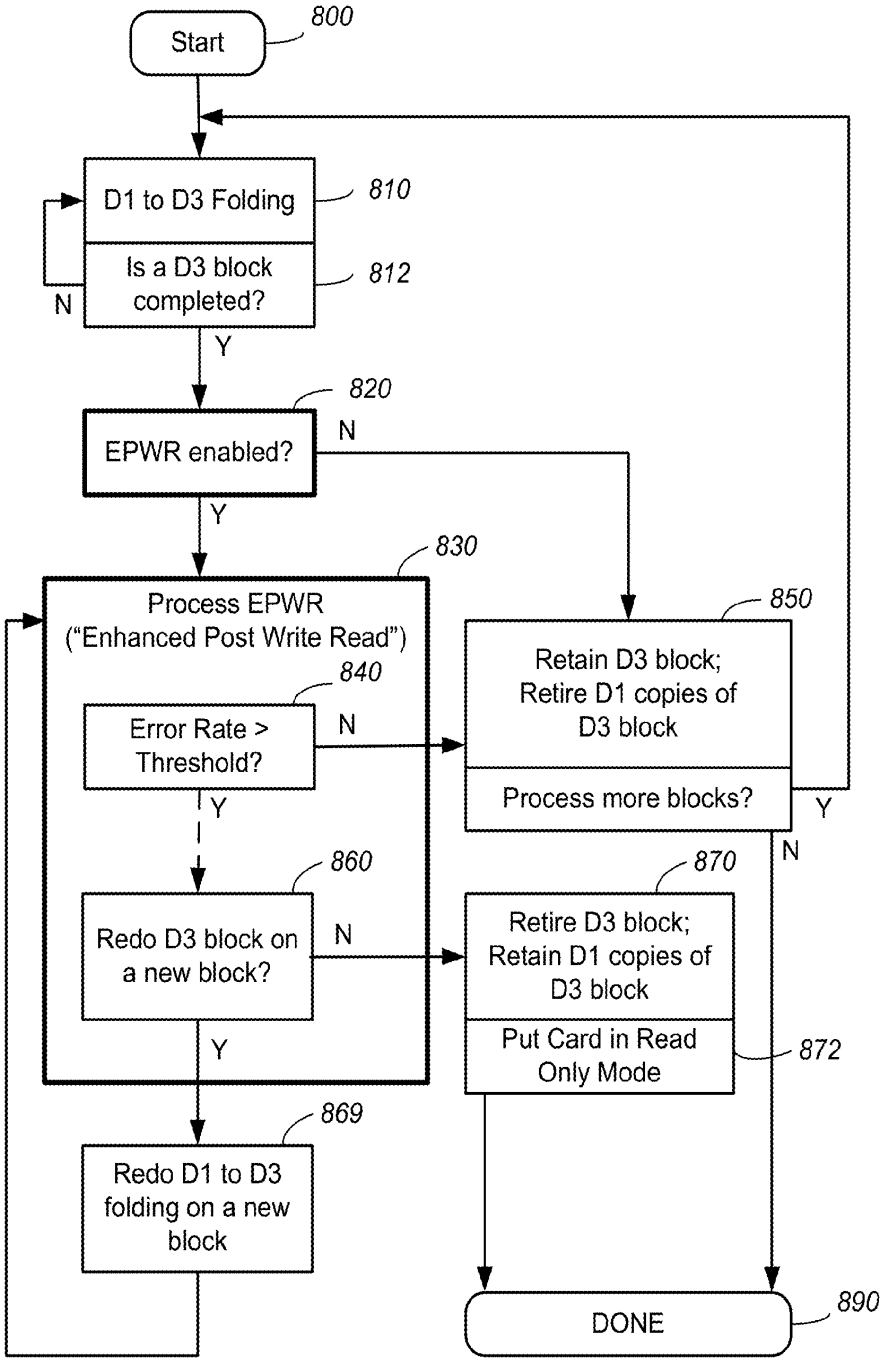

Start
800
D1 to D3 Folding
810
Is a D3 block completed?
812
N
Y
EPWR enabled?
820
N
Y
Process EPWR ("Enhanced Post Write Read")
830
Error Rate > Threshold?
840
N
Y
Redo D3 block on a new block?
860
N
Y
Redo D1 to D3 folding on a new block
869
Retain D3 block; Retire D1 copies of D3 block
850
Process more blocks?
Y
N
Retire D3 block; Retain D1 copies of D3 block
870
Put Card in Read Only Mode
872
DONE
890

FIG. 22A

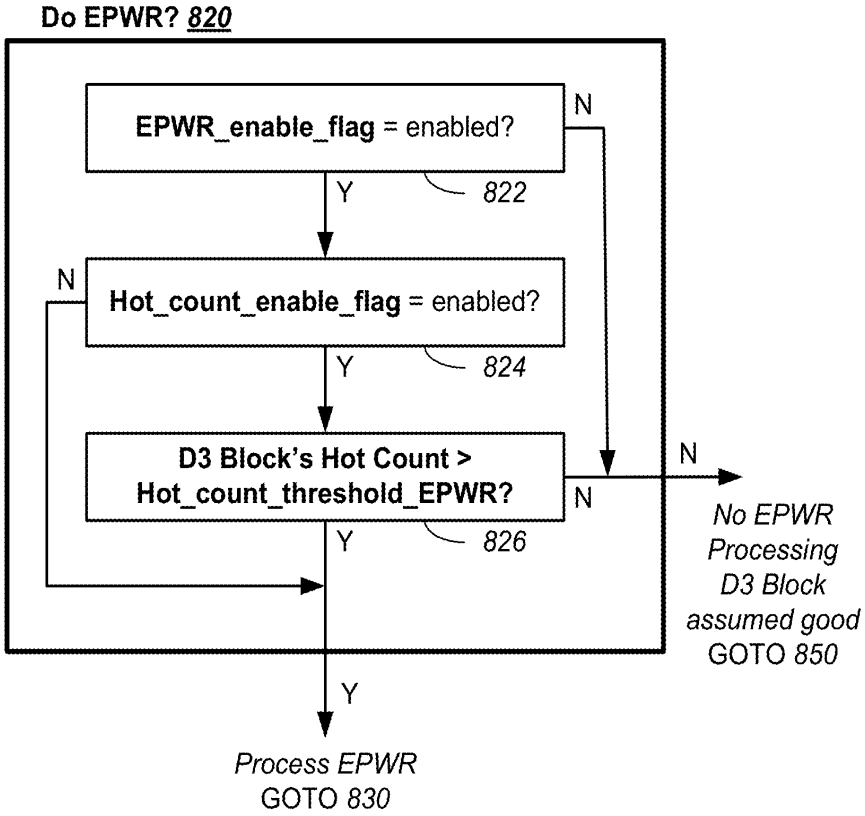

Do EPWR? 820
EPWR_enable_flag = enabled?
N
Y
822
N
Hot_count_enable_flag = enabled?
Y
824
D3 Block's Hot Count > Hot_count_threshold_EPWR?
N
N
Y
826
No EPWR Processing D3 Block assumed good GOTO 850
Y
Process EPWR GOTO 830

FIG. 22B

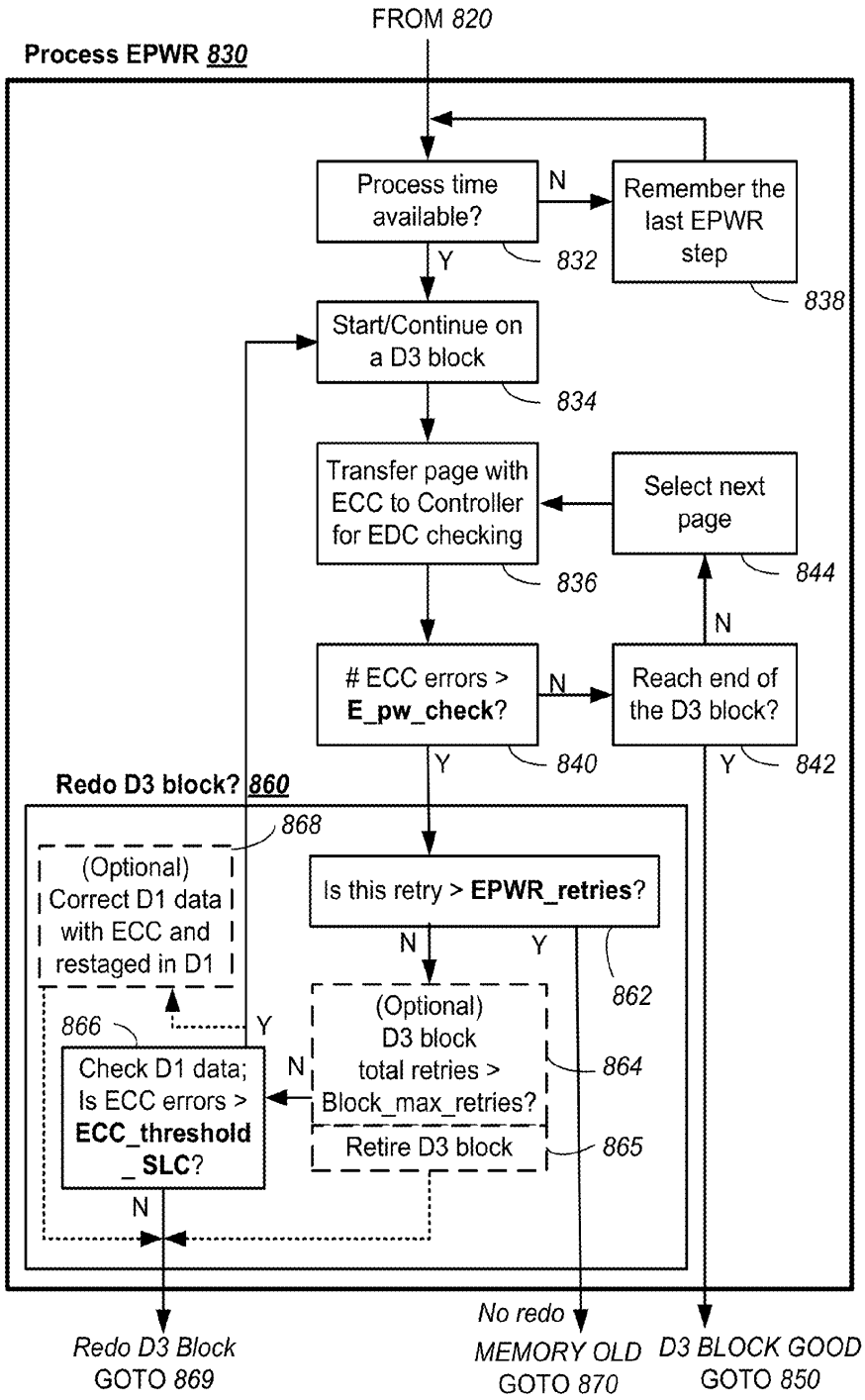
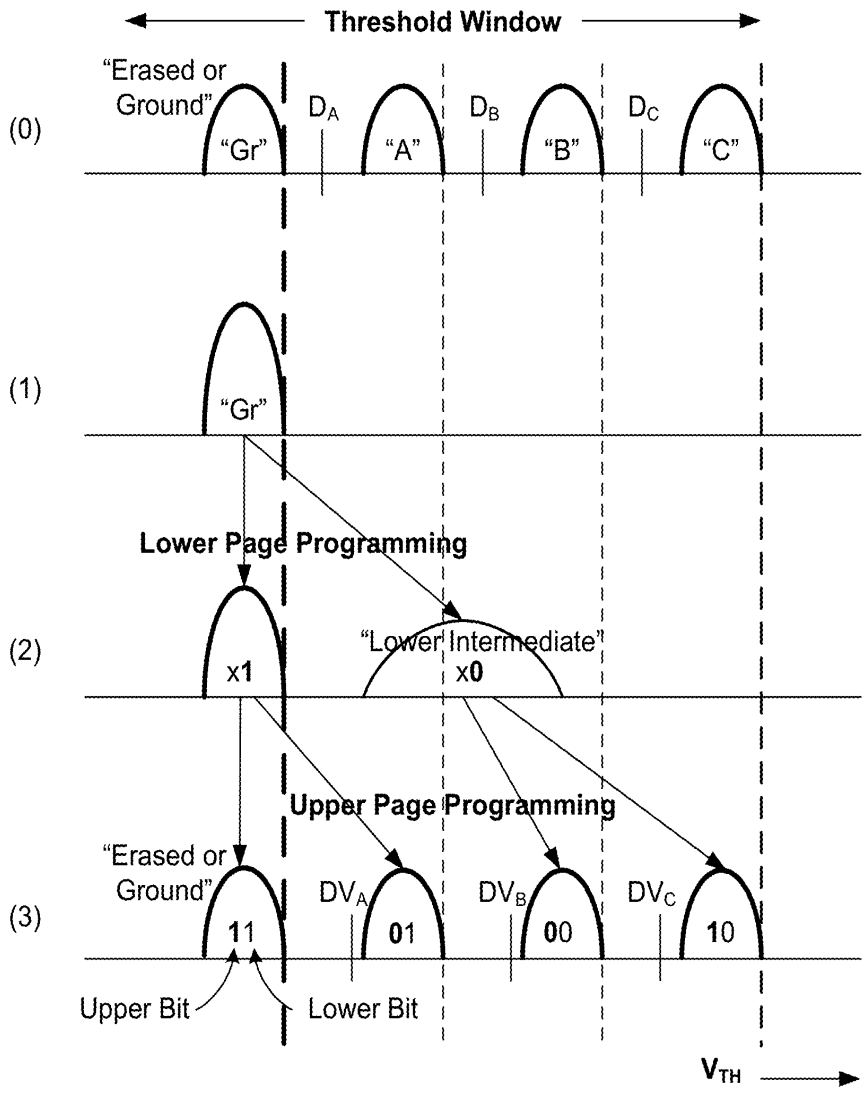
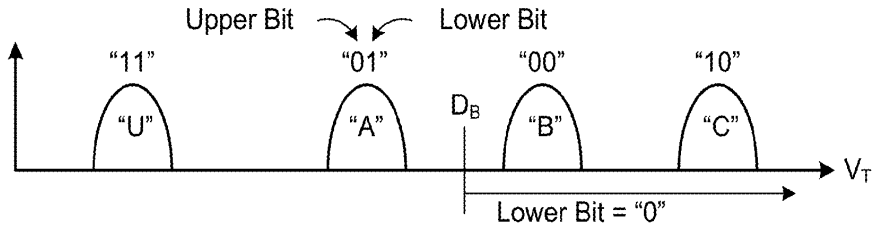

FROM 820
Process EPWR 830
Process time available?
N
Remember the last EPWR step
Y
832
838
Start/Continue on a D3 block
834
Transfer page with ECC to Controller for EDC checking
Select next page
836
844
N
ECC errors > E_pw_check?
N
Reach end of the D3 block?
Y
840
Y
842
Redo D3 block? 860
868
(Optional) Correct D1 data with ECC and restaged in D1
Is this retry > EPWR_retries?
N
Y
862
866
Y
(Optional) D3 block total retries > Block_max_retries?
N
864
Check D1 data; Is ECC errors > ECC_threshold _ SLC?
Retire D3 block
865
N
Redo D3 Block
GOTO 869
No redo
MEMORY OLD
GOTO 870
D3 BLOCK GOOD
GOTO 850

FIG. 22C



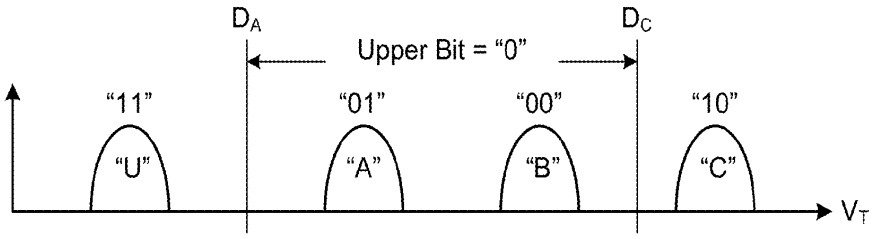
Logical-Page-by-Logical-Page Programming (2-bit LM Gray Code)

FIG. 23



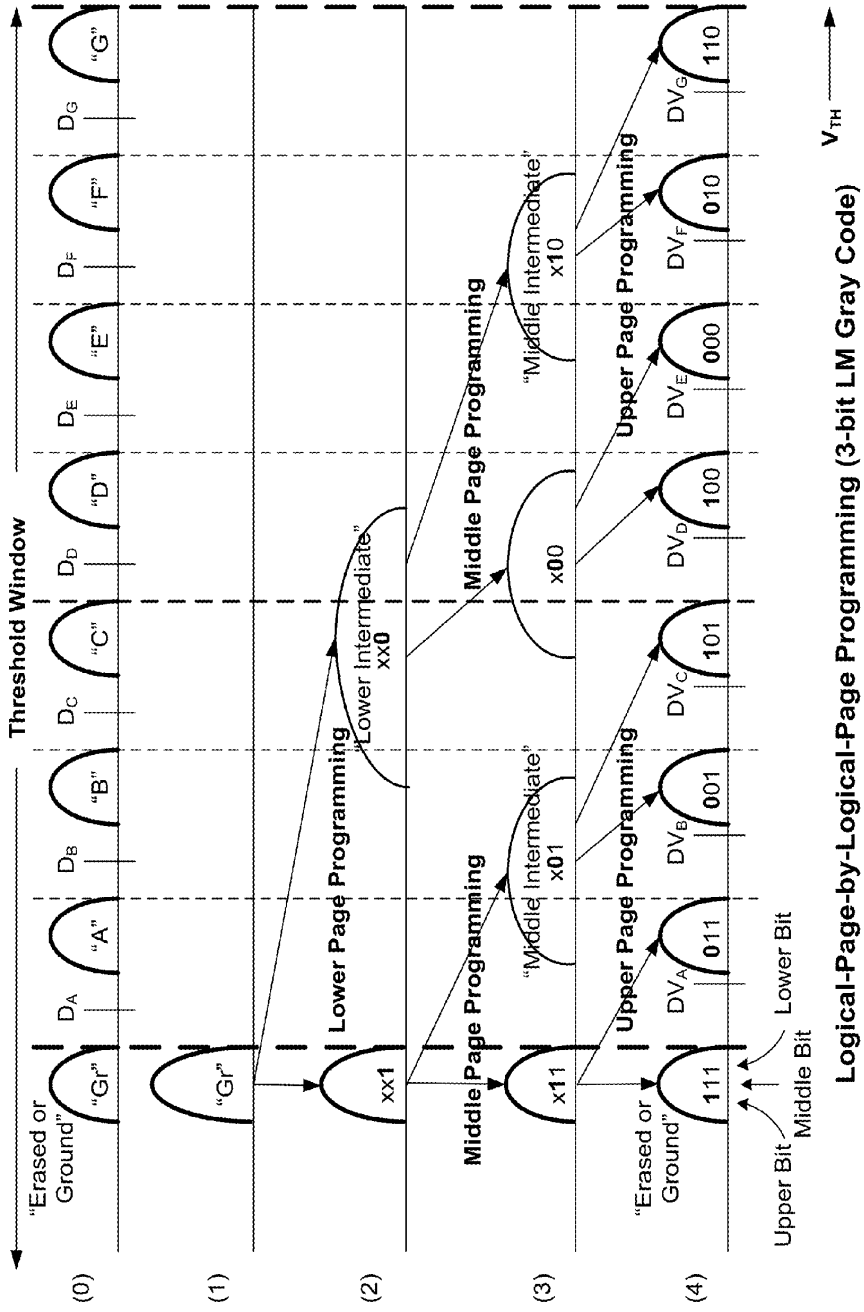
Lower Page Read (LM Gray Code)

FIG. 24A



Upper Page Read (LM Gray Code)

FIG. 24B



Logical-Page-by-Logical-Page Programming (3-bit LM Gray Code)

FIG. 25

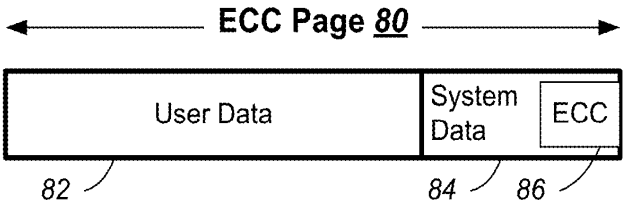


FIG. 26A

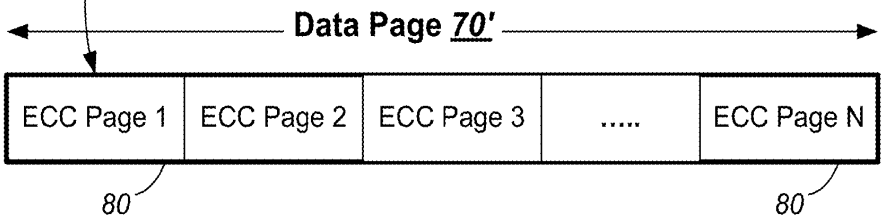
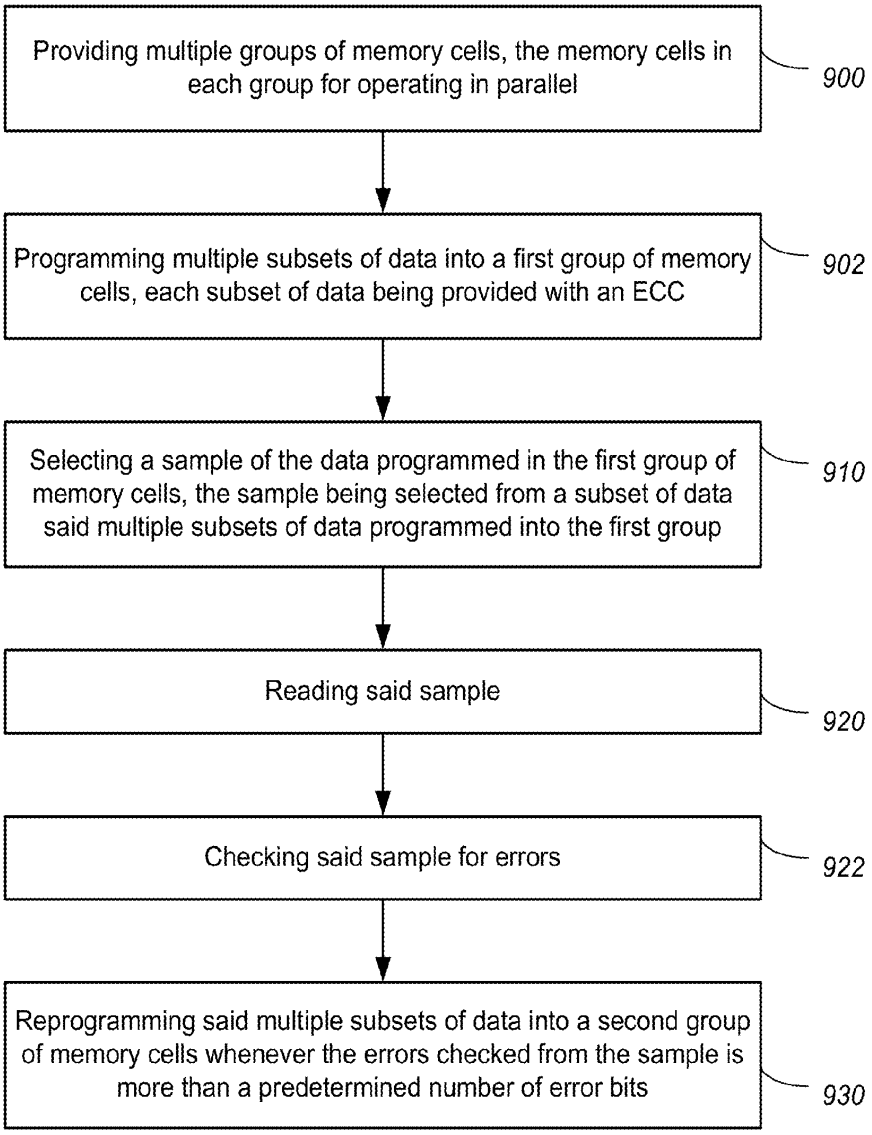


FIG. 26B



Accelerated PWR

FIG. 27

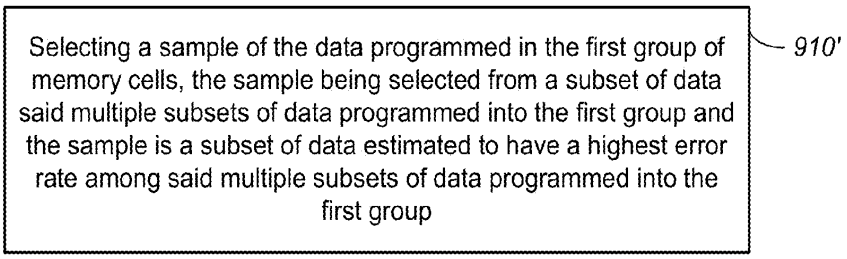
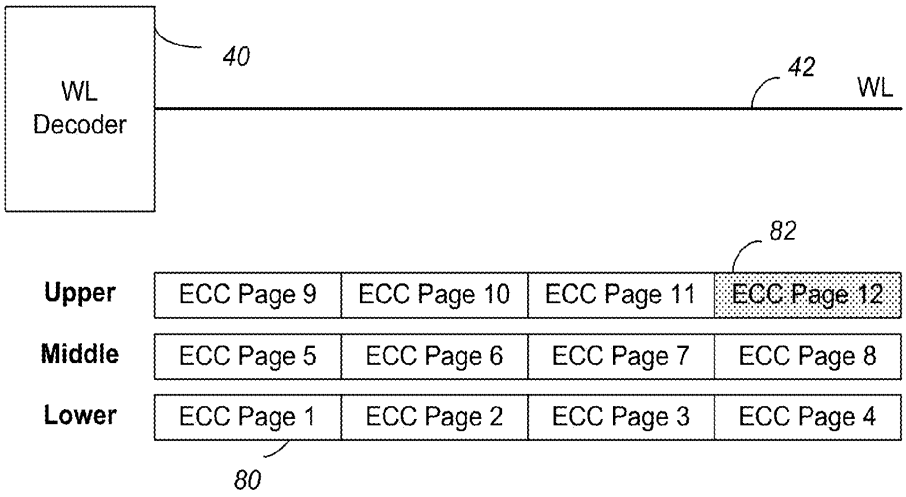


FIG. 28



3 Data Pages stored on WL

FIG. 29

NON-VOLATILE MEMORY AND METHOD WITH ACCELERATED POST-WRITE READ TO MANAGE ERRORS

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part of U.S. application Ser. No. 12/642,728 filed on Dec. 18, 2009 now U.S. Pat. No. 8,423,866, which is a continuation-in-part of U.S. application Ser. No. 12/607,522 filed on Oct. 28, 2009, now U.S. Pat. No. 8,214,700.

BACKGROUND OF THE INVENTION

This application relates to the operation of re-programmable non-volatile memory systems such as semiconductor flash memory, and, more specifically, to handling and efficient managing of errors in memory operations.

Solid-state memory capable of nonvolatile storage of charge, particularly in the form of EEPROM and flash EEPROM packaged as a small form factor card, has recently become the storage of choice in a variety of mobile and handheld devices, notably information appliances and consumer electronics products. Unlike RAM (random access memory) that is also solid-state memory, flash memory is non-volatile, and retaining its stored data even after power is turned off. Also, unlike ROM (read only memory), flash memory is rewritable similar to a disk storage device. In spite of the higher cost, flash memory is increasingly being used in mass storage applications. Conventional mass storage, based on rotating magnetic medium such as hard drives and floppy disks, is unsuitable for the mobile and handheld environment. This is because disk drives tend to be bulky, are prone to mechanical failure and have high latency and high power requirements. These undesirable attributes make disk-based storage impractical in most mobile and portable applications. On the other hand, flash memory, both embedded and in the form of a removable card are ideally suited in the mobile and handheld environment because of its small size, low power consumption, high speed and high reliability features.

Flash EEPROM is similar to EEPROM (electrically erasable and programmable read-only memory) in that it is a non-volatile memory that can be erased and have new data written or "programmed" into their memory cells. Both utilize a floating (unconnected) conductive gate, in a field effect transistor structure, positioned over a channel region in a semiconductor substrate, between source and drain regions. A control gate is then provided over the floating gate. The threshold voltage characteristic of the transistor is controlled by the amount of charge that is retained on the floating gate. That is, for a given level of charge on the floating gate, there is a corresponding voltage (threshold) that must be applied to the control gate before the transistor is turned "on" to permit conduction between its source and drain regions. In particular, flash memory such as Flash EEPROM allows entire blocks of memory cells to be erased at the same time.

The floating gate can hold a range of charges and therefore can be programmed to any threshold voltage level within a threshold voltage window. The size of the threshold voltage window is delimited by the minimum and maximum threshold levels of the device, which in turn correspond to the range of the charges that can be programmed onto the floating gate. The threshold window generally depends on the memory device's characteristics, operating conditions and history.

Each distinct, resolvable threshold voltage level range within the window may, in principle, be used to designate a definite memory state of the cell.

It is common in current commercial products for each storage element of a flash EEPROM array to store a single bit of data by operating in a binary mode, where two ranges of threshold levels of the storage element transistors are defined as storage levels. The threshold levels of transistors correspond to ranges of charge levels stored on their storage elements. In addition to shrinking the size of the memory arrays, the trend is to further increase the density of data storage of such memory arrays by storing more than one bit of data in each storage element transistor. This is accomplished by defining more than two threshold levels as storage states for each storage element transistor, four such states (2 bits of data per storage element) now being included in commercial products. More storage states, such as 16 states per storage element, are also being implemented. Each storage element memory transistor has a certain total range (window) of threshold voltages in which it may practically be operated, and that range is divided into the number of states defined for it plus margins between the states to allow for them to be clearly differentiated from one another. Obviously, the more bits a memory cell is configured to store, the smaller is the margin of error it has to operate in.

The transistor serving as a memory cell is typically programmed to a "programmed" state by one of two mechanisms. In "hot electron injection," a high voltage applied to the drain accelerates electrons across the substrate channel region. At the same time a high voltage applied to the control gate pulls the hot electrons through a thin gate dielectric onto the floating gate. In "tunneling injection," a high voltage is applied to the control gate relative to the substrate. In this way, electrons are pulled from the substrate to the intervening floating gate. While the term "program" has been used historically to describe writing to a memory by injecting electrons to an initially erased charge storage unit of the memory cell so as to alter the memory state, it has now been used interchangeable with more common terms such as "write" or "record."

The memory device may be erased by a number of mechanisms. For EEPROM, a memory cell is electrically erasable, by applying a high voltage to the substrate relative to the control gate so as to induce electrons in the floating gate to tunnel through a thin oxide to the substrate channel region (i.e., Fowler-Nordheim tunneling.) Typically, the EEPROM is erasable byte by byte. For flash EEPROM, the memory is electrically erasable either all at once or one or more minimum erasable blocks at a time, where a minimum erasable block may consist of one or more sectors and each sector may store 512 bytes or more of data.

The memory device typically comprises one or more memory chips that may be mounted on a card. Each memory chip comprises an array of memory cells supported by peripheral circuits such as decoders and erase, write and read circuits. The more sophisticated memory devices also come with a controller that performs intelligent and higher level memory operations and interfacing.

There are many commercially successful non-volatile solid-state memory devices being used today. These memory devices may be flash EEPROM or may employ other types of nonvolatile memory cells. Examples of flash memory and systems and methods of manufacturing them are given in U.S. Pat. Nos. 5,070,032, 5,095,344, 5,315,541, 5,343,063, and 5,661,053, 5,313,421 and 6,222,762. In particular, flash memory devices with NAND string structures are described in U.S. Pat. Nos. 5,570,315, 5,903,495, 6,046,935. Also non-

volatile memory devices are also manufactured from memory cells with a dielectric layer for storing charge. Instead of the conductive floating gate elements described earlier, a dielectric layer is used. Such memory devices utilizing dielectric storage element have been described by Eitan et al., "NROM: A Novel Localized Trapping, 2-Bit Nonvolatile Memory Cell," IEEE Electron Device Letters, vol. 21, no. 11, November 2000, pp. 543-545. An ONO dielectric layer extends across the channel between source and drain diffusions. The charge for one data bit is localized in the dielectric layer adjacent to the drain, and the charge for the other data bit is localized in the dielectric layer adjacent to the source. For example, U.S. Pat. Nos. 5,768,192 and 6,011,725 disclose a nonvolatile memory cell having a trapping dielectric sandwiched between two silicon dioxide layers. Multi-state data storage is implemented by separately reading the binary states of the spatially separated charge storage regions within the dielectric.

In order to improve read and program performance, multiple charge storage elements or memory transistors in an array are read or programmed in parallel. Thus, a "page" of memory elements are read or programmed together. In existing memory architectures, a row typically contains several interleaved pages or it may constitute one page. All memory elements of a page will be read or programmed together.

Errors in Written Data

In the types of memory systems described herein, as well as in others, including magnetic disc storage systems, the integrity of the data being stored is maintained by use of an error correction technique. Most commonly, an error correction code (ECC) is calculated for each sector or other unit of data that is being stored at one time, and that ECC is stored along with the data. The ECC is most commonly stored together with a unit group of user data from which the ECC has been calculated. The unit group of user data may be a sector or a multi-sector page. When this data is read from the memory, the ECC is used to determine the integrity of the user data being read. Erroneous bits of data within the unit group of data can often be corrected by use of the ECC.

The trend is to reduce the size of the memory systems in order to be able to put more memory cells in the system and to make the system as small as possible to fit in smaller host devices. Memory capacity is increased by a combination of higher integration of circuits and configuring each memory cell to store more bits of data. Both techniques require the memory to operate with increasing tighter margin of error. This in turn places more demand on the ECC to correct errors.

The ECC can be designed to correct a predetermined number of error bits. The more bits it has to correct, the more complex and computationally intensive will the ECC be. For quality assurance, conventional ECC is designed based on the expected worst-case cell error rate at the end of life of the memory device. Thus, they have to correct a maximum number of error bits up to the far tail end of a statistical population of error rate.

As the flash memory ages, its error rate increases rapidly near the end of life of the device. Thus a powerful ECC designed for the worst-case will only be called to apply its full capacity at the end of life of the memory device.

Using ECC to correct a worst-case number of error bits will consume a great amount processing time. The more bits it has to correct, the more computational time is required. The memory performance will be degraded. Additional dedicated hardware may be implemented to perform the ECC in a reasonable amount of time. Such dedicated hardware can take up a considerable amount of space on the controller ASIC chip. Moreover, for most of the life time of the device, the ECC is only marginally utilized, resulting in its large overheads being wasted and realizing no real benefits.

Thus, there is a need to provide a nonvolatile memory of high storage capacity without the need for a resource-intensive ECC over designed for the worse-case.

SUMMARY OF THE INVENTION

Adaptively Rewrite Data from a Higher Density Memory Portion to a Lower Error Rate Memory Portion to Control Error Rate

According to a general aspect of the invention, a post-write-read error management is provided in that a flash memory having an array of memory cells is configured with a first portion and a second portion. The second portion stores data at higher density but operates with a smaller margin of errors compared to the first portion. Data is written to the second portion for efficient storage. Afterwards, the data is read back in a post-write read operation to check for excessive error bits. If the error bits exceeded a predetermined amount, the data is rewritten or kept at the less error-prone first portion. This places a limit on the maximum number of error bits arising from writing data to the memory. In a statistical distribution of error rates, the limit represents a limit on the number standard derivations of the distribution so that the far tail-end of the distribution (with higher error rates) can be ignored. This allows a smaller and more efficient error correction code ("ECC") to be designed for correcting a smaller number of errors bits, thereby improving the performance and reducing the cost of the memory.

In one preferred embodiment, the first portion has each memory cell storing one bit of data and the second portion has each memory cell storing more than one bit of data.

In an alternative embodiment, the first portion serves as a cache for incoming data, so a cache copy of the input data is programmed into the cache. Then a first copy of data is programmed into the second portion. If the post-write read has not detected an excessive amount of error in the first copy, the first copy will be deemed valid and subsequent access will be directed to access the first copy. On the other hand, if the post-write read has detected an excessive amount of error in the first copy, the cached copy in the first portion will replace the first copy in the second portion as valid data. The first copy will become obsolete and subsequent access will be directed to the cached copy.

In the preferred embodiment, the first portion is further provided with a first section and a second section. The incoming data is cached in the first section of the first portion and a first copy of the data is written to the second portion. Afterwards, the first copy in the second portion is read back to check for excessive error bits. If the error bits exceeded a predetermined amount, a second copy of the in coming data is written to the second section of the first portion.

According to another preferred embodiment, the memory array is provided with a set of data latches on an integrated circuit chip, the checking of the error bits in the first copy is accomplished by loading the first copy and the cached copy into the set of data latches and making a comparison at the set of data latches.

In an alternative embodiment, after the post-write read has detected an excessive amount of error in the first copy, the cached copy in the first portion will replace the first copy in the second portion as valid data. The first copy will become obsolete and a directory in a block management system embodied in the firmware of the controller (see FIG. **1**) will be update to direct subsequent access to the cached copy.

Thus, when writing to a high density storage portion of the memory, a post-write read checks if the error rate is within a prescribed limit. If not the data is rewritten to or kept at another, less error-prone, portion of the memory. The less error-prone portion typically has each memory cell storing less data bits per cell compared to the high density storage portion. By providing a mechanism to control and limit the errors arising after writing to a high density memory, and providing a second chance to rewrite data with less error if the copy in the high density memory has excessive errors, the number of errors bits that an ECC will need to correct is significantly reduced. The advantage is gained at the slight expense of an additional post-write read and infrequent additional rewrites to a less density memory portion.

For example, the high density storage portion of the memory has each memory cell storing 3 bits of data. The less error-prone portion has each memory cell storing 1 bit of data. It is estimated that by limiting the error rates to within three standard deviations (3σ) instead of the conventional worst-case approach of 6σ, the ECC needs only correct 4 bits instead of the 42 bits. Limiting to 3σ is that 0.13% of the population is expected to have error rates exceeding 4 bits. The cost incurred is that data written in high density storage having more than 4 error bits (0.13% of the population) will simply have the data rewritten to or kept at lower density storage to avoid exceeding the error limit. In comparison, in the conventional approach, an ECC designed for the worst case to correct 42 bits for write errors carries a large overhead at all time, even though for most of that time it only needs to correct far less number of bits.

Enhanced Post-Write-Read Error Management

In another aspect of the invention, an enhanced post-write read error management is implemented. The post-write read error management is not enabled at the beginning of life of a memory device. The error rate of the memory device at the beginning of life is very low and there is no need to operate the post-write read. This avoids wasting time to do post-write read. As the memory device ages through use, the enhanced post-write read and error management of the invention is enabled at a predetermined age of the device.

In a preferred embodiment, the age of the memory device is determined by a hot count maintained with each erase block of memory cells. The hot count tracks the endurance or the number of times the erase block has been cycled through erase and program operations. Whenever a hot count of an erase block passes a predetermined hot count threshold, the enhanced post-write-read error management will commence and operate until the end of life of the memory device.

In a preferred embodiment of yet another aspect of the invention, the high density storage portion of the memory (D**3**) has each memory storing 3 bits of data. The less error-prone, low density storage portion of the memory (D**1**) has each memory cell storing 1 bit of data. Input data is first staged in D**1** and subsequently folded into D**3**. When the enhanced post-write-read error management is enabled, a current, filled block in D**3** is read back; and if the error rate exceeds a predetermined threshold, the current D**3** block is rejected and a retry takes place with data being refolded into a new D**3** block. The new D**3** block is again read back and checked for excessive error rate. If the new D**3** block passes, then it has good data and the original data in D**1** is made obsolete. If the new D**3** block again shows excessive error rate, the new D**3** block is again discarded. If the excessive error rate persists after a predetermined number of retries, no further retry is attempted and the D**1** to D**3** folding operation is abandoned with the original data kept at D**1**. At this point the memory device is deemed too old for further programming operations and is made read-only to preserve the integrity of the existing data stored in the memory device.

Accelerated Post-Write Read

According to another aspect of the invention, instead of post-write reading every memory cells to check what have been written, which could consume a lot of time and system resources, the post-write read is only performed on a small sample of memory cells representing a population of written memory cells. When the post-write read of the sample yields an error rate within a predetermined value, the population is assumed to pass the check. Otherwise, the data previously written on the population of cells are deemed to have too much error and are either rewritten again to a different location in the same area or to another area of the memory with intrinsic lower error rate.

Data errors in non-volatile memory inevitably increase with usage and with higher density of bits stored per cell. The memory is configured to have a first portion operating with less error but of lower density storage, and a second portion operating with a higher density but less robust storage. An error management provides reading and checking the copy after copying to the second portion. If the copy has excessive error bits, it is repeated in a different location either in the second or first portion. The reading and checking of the copy is accelerated by reading only a sample of it. The sample is selected from a subset of the copy having its own ECC and estimated to represent a worst error rate among the copy it is sampling.

In one embodiment, the sample to be check is a subset of all the ECC pages written to a group of cell on a word line. In particular, the subset is one among all the ECC pages that is estimated to have a highest error rate.

In another embodiment, the sample to be check is a subset of all the ECC pages written to a group of cells in a block. The block has all cells in it erasable together. In particular, the subset is one among all the ECC pages that is estimated to have a highest error rate.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates a host in communication with a memory device in which the features of the present invention are embodied.

FIG. **2** illustrates schematically a non-volatile memory cell.

FIG. **3** illustrates an example of an NOR array of memory cells.

FIG. **4** illustrates a page of memory cells, organized for example in the NAND configuration, being sensed or programmed in parallel.

FIG. **5**A illustrates in more detail the sense modules shown in FIG. **1** to contain a bank of p sense modules across an array of memory cells.

FIG. **5**B illustrates a sense module including a sense amplifier.

FIG. **6** illustrates schematically an example of a memory array organized in erasable blocks.

FIG. **7** illustrates a binary memory having a population of cells with each cell being in one of two possible states.

FIG. **8** illustrates a multi-state memory having a population of cells with each cell being in one of eight possible states.

FIG. **9** illustrates schematically a data page containing an ECC field.

FIG. **10**A shows a normal distribution of error rate, with the percentage of the population in various ranges of standard deviations σ.

FIG. **10**B illustrate the distribution of FIG. **10**A in a table format.

FIG. **11** is a table listing the main sources of errors for a flash memory.

FIG. **12** is a table showing estimated total errors for an example memory device at the beginning and end of its life.

FIG. **13** is a table illustrating that a conventional ECC must be designed to correct the worst-case total error E_{TOT}.

FIG. **14**A illustrates a memory array being partitioned into two portions according to a preferred embodiment of the invention.

FIG. **14**B illustrates a rewrite of a second copy of the data page into the first portion of the memory array of FIG. **14**A.

FIG. **15** is a flow diagram illustrating the process of post-write read and adaptive rewrite according to the embodiment described in FIG. **14**A and FIG. **14**B.

FIG. **16**A illustrates a memory array being partitioned into two portions and the first portion further provided with a cache section and rewrite section, according to a preferred embodiment of the invention.

FIG. **16**B illustrates a page compare technique according a preferred embodiment of the post-write read. FIG. **16**C illustrates a rewrite to the first portion after a post-write read has determined an excessive amount of error in the data page in the second portion.

FIG. **17** is a flow diagram illustrating the process of post-write read and adaptive rewrite according to the embodiment described in FIG. **16**A to FIG. **16**C.

FIG. **18** illustrates a memory organized into erase blocks.

FIG. **19** is a flow diagram illustrating the error management being enabled when the memory device has aged to a predetermined degree as determined by a hot count.

FIG. **20**A illustrates a memory array being partitioned into two portions according to a preferred embodiment of the invention.

FIG. **20**B illustrates another example in which the D**3** block of FIG. **20**A fails a post-write-read test.

FIG. **20**C illustrates another example in which the new D**3** block of FIG. **20**B fails the post-write read test again.

FIG. **21** is a table illustrating example parameters associated with the enhanced post-write-read error management. The table is preferably maintained in the file system configuration file stored in memory.

FIG. **22**A is a flow diagram illustrating a preferred implementation of the EPWR error management as applied to a memory having D**1** to D**3** folding.

FIG. **22**B illustrates in more detail the device-age-dependent enablement feature of the enhanced post-write-read error management.

FIG. **22**C illustrates in more detail a preferred implementation of the enhanced post-write-read error management.

FIGS. **23**(**0**)-**23**(**3**) illustrate a logical page by page programming of a 4-state memory encoded with a preferred 2-bit logical code ("LM" code).

FIG. **24**A illustrates the read operation that is required to discern the lower bit of the 4-state memory encoded with the 2-bit LM code.

FIG. **24**B illustrates the read operation that is required to discern the upper bit of the 4-state memory encoded with the 2-bit LM code.

FIGS. **25**(**0**)-**25**(**4**) illustrate the programming of an 8-state memory encoded with a preferred 3-bit logical code ("LM" code).

FIG. **26**A illustrates schematically an ECC page containing an ECC field similar to that shown in FIG. **9**.

FIG. **26**B illustrates a plurality of ECC pages constituting a data page.

FIG. **27** is a flow chart illustrating the general embodiment of accelerated PWR.

FIG. **28** is a flow chart illustrating a preferred embodiment of accelerated PWR illustrated in FIG. **27**.

FIG. **29** illustrates a sample selected for post-write read after a group of 3-bit memory cells on a word line has been written.

DETAILED DESCRIPTION

Memory System

FIG. **1** illustrates a host in communication with a memory device in which the features of the present invention are embodied. The host **80** typically sends data to be stored at the memory device **90** or retrieves data by reading the memory device **90**. The memory device **90** includes one or more memory chip **100** managed by a controller **102**. The memory chip **100** includes a memory array **200** of memory cells with each cell capable of being configured as a multi-level cell ("MLC") for storing multiple bits of data. The memory chip also includes peripheral circuits such as sense modules **480**, data latches **430** and I/O circuits **440**. An on-chip control circuitry **110** controls low-level memory operations of each chip. The control circuitry **110** is an on-chip controller that cooperates with the peripheral circuits to perform memory operations on the memory array **200**. The control circuitry **110** typically includes a state machine **112** to provide chip level control of memory operations.

In many implementations, the host **80** communicates and interacts with the memory chip **100** via the controller **102**. The controller **102** co-operates with the memory chip and controls and manages higher level memory operations. For example, in a host write, the host **10** sends data to be written to the memory array **100** in logical sectors allocated from a file system of the host's operating system. A memory block management system implemented in the controller stages the sectors and maps and stores them to the physical structure of the memory array.

A preferred block management system is disclosed in United States Patent Application Publication No. 2010/0172180 A1, published on Jul. 8, 2010, the entire disclosure of which is incorporated herein by reference.

A firmware **60** provides codes to implement the functions of the controller **102**. An error correction code ("ECC") processor **62** processes ECC during operations of the memory device. In another embodiment, the controller **102** is implemented within the host.

Physical Memory Structure

FIG. **2** illustrates schematically a non-volatile memory cell. The memory cell **10** can be implemented by a field-effect transistor having a charge storage unit **20**, such as a floating gate or a dielectric layer. The memory cell **10** also includes a source **14**, a drain **16**, and a control gate **30**.

There are many commercially successful non-volatile solid-state memory devices being used today. These memory devices may employ different types of memory cells, each type having one or more charge storage element. Typical non-volatile memory cells include EEPROM and flash EEPROM. Examples of EEPROM cells and methods of manufacturing them are given in U.S. Pat. No. 5,595,924. Examples of flash EEPROM cells, their uses in memory systems and methods of manufacturing them are given in U.S. Pat. Nos. 5,070,032, 5,095,344, 5,315,541, 5,343,063, 5,661,053, 5,313,421 and 6,222,762. In particular, examples of memory devices with NAND cell structures are described in U.S. Pat. Nos. 5,570,315, 5,903,495, 6,046,935. Also,

examples of memory devices utilizing dielectric storage element have been described by Eitan et al., "NROM: A Novel Localized Trapping, 2-Bit Nonvolatile Memory Cell," IEEE Electron Device Letters, vol. 21, no. 11, November 2000, pp. 543-545, and in U.S. Pat. Nos. 5,768,192 and 6,011,725.

In practice, the memory state of a cell is usually read by sensing the conduction current across the source and drain electrodes of the cell when a reference voltage is applied to the control gate. Thus, for each given charge on the floating gate of a cell, a corresponding conduction current with respect to a fixed reference control gate voltage may be detected. Conversely, a threshold voltage is defined as the voltage on the control gate that will just turn on the cell with the given charge. Similarly, the range of charge programmable onto the floating gate defines a corresponding threshold voltage window or a corresponding conduction current window.

Alternatively, instead of detecting the conduction current among a partitioned current window, it is possible to set the threshold voltage for a given memory state under test at the control gate and detect if the conduction current is lower or higher than a threshold current. In one implementation the detection of the conduction current relative to a threshold current is accomplished by examining the rate the conduction current is discharging through the capacitance of the bit line or a known capacitor.

As can be seen from the description above, the more states a memory cell is made to store, the more finely divided is its threshold window. For example, a memory device may have memory cells having a threshold window that ranges from −1.5V to 5V. This provides a maximum width of 6.5V. If the memory cell is to store 16 states, each state may occupy from 200 mV to 300 mV in the threshold window. This will require higher precision in programming and reading operations in order to be able to achieve the required resolution.

The memory array **200** is typically organized as a two-dimensional array of memory cells arranged in rows and columns and addressable by word lines and bit lines. The array can be formed according to an NOR type or an NAND type architecture.

FIG. **3** illustrates an example of an NOR array of memory cells. In the memory array **200**, each row of memory cells are connected by their sources **14** and drains **16** in a daisy-chain manner. This design is sometimes referred to as a virtual ground design. The cells **10** in a row have their control gates **30** connected to a word line, such as word line **42**. The cells in a column have their sources and drains respectively connected to selected bit lines, such as bit lines **34** and **36**.

FIG. **4** illustrates a page of memory cells, organized for example in the NAND configuration, being sensed or programmed in parallel. FIG. **4** essentially shows a bank of NAND strings **50** in the memory array **200**. A NAND string **50** comprises of a series of memory transistors (e.g., 4, 8, 16 or higher) daisy-chained by their sources and drains. A pair of select transistors S**1**, S**2** controls the memory transistors chain's connection to the external via the NAND string's source terminal and drain terminal respectively. In a memory array, when the source select transistor S**1** is turned on, the source terminal is coupled to a source line **34**. Similarly, when the drain select transistor S**2** is turned on, the drain terminal of the NAND string is coupled to a bit line **36** of the memory array. Each memory transistor **10** in the chain acts as a memory cell. It has a charge storage element **20** to store a given amount of charge so as to represent an intended memory state. A control gate of each memory transistor allows control over read and write operations. The control gates of corresponding memory transistors of a row of NAND string are all connected to the same word line (such as WL**0**, WL**1**, ...) Similarly, a control gate of each of the select transistors S**1**, S**2** (accessed via select lines SGS and SGD respectively) provides control access to the NAND string via its source terminal and drain terminal respectively.

When an addressed memory transistor **10** within an NAND string is read or is verified during programming, its control gate is supplied with an appropriate voltage via a common word line. At the same time, the rest of the non-addressed memory transistors in the NAND string **50** are fully turned on by application of sufficient voltage on their control gates. In this way, a conductive path is effective created from the source of the individual memory transistor to the source terminal of the NAND string and likewise for the drain of the individual memory transistor to the drain terminal of the cell. Memory devices with such NAND string structures are described in U.S. Pat. Nos. 5,570,315, 5,903,495, 6,046,935.

A "page" such as the page **70**, is a group of memory cells enabled to be sensed or programmed in parallel. This is accomplished by a corresponding page of sense amplifiers. For example, the page **70** is along a row and is sensed by a sensing voltage applied to the control gates of the cells of the page connected in common to the word line WL**3**. Along each column, each cell such as cell **10** is accessible by a sense amplifier via a bit line **36**. The page referred to above is a physical page memory cells or sense amplifiers. Depending on context, in the case where each cell is storing.

Sensing Circuits and Techniques

FIG. **5**A illustrates in more detail the sense modules shown in FIG. **1** to contain a bank of p sense modules across an array of memory cells. The entire bank of p sense modules **480** operating in parallel allows a group (or physical page) of p cells **10** along a row to be read or programmed in parallel. Essentially, sense module **1** will sense a current I_1 in cell **1**, sense module **2** will sense a current I_2 in cell **2**, . . . , sense module p will sense a current I_p in cell p, etc. The total cell current i_{TOT} for the page flowing out of the source line **34** into an aggregate node CLSRC and from there to ground will be a summation of all the currents in the p cells.

In conventional memory architecture, a row of memory cells with a common word line forms two or more pages, where the memory cells in a page are read and programmed in parallel. In the case of a row with two pages, one page is accessed by even bit lines and the other page is accessed by odd bit lines. A physical page of sensing circuits is coupled to either the even bit lines or to the odd bit lines at any one time.

In currently produced chips, the physical page may be 64 k or larger. In the preferred embodiment, the group is a run of the entire row of cells. This is the so-called "all bit-line" architecture in which the page is constituted from a row of contiguous memory cells coupled respectively to contiguous bit lines.

FIG. **5**B illustrates a sense module including a sense amplifier. The sense amplifier **490** detects the conduction current of a cell is above or below a reference level. The sensed results are latches in a corresponding set of latches **430** (see FIG. **1**).

Erase Blocks

One important difference between flash memory and other type of memory is that a cell must be programmed from the erased state. That is the floating gate must first be emptied of charge. Programming then adds a desired amount of charge back to the floating gate. It does not support removing a portion of the charge from the floating to go from a more programmed state to a lesser one. This means that update data cannot overwrite existing one and must be written to a previous unwritten location.

Furthermore erasing is to empty all the charges from the floating gate and generally takes appreciably time. For that reason, it will be cumbersome and very slow to erase cell by cell or even page by page. In practice, the array of memory cells is divided into a large number of blocks of memory cells. As is common for flash EEPROM systems, the block is the unit of erase. That is, each block contains the minimum number of memory cells that are erased together.

FIG. **6** illustrates schematically an example of a memory array organized in erasable blocks. Programming of charge storage memory devices can only result in adding more charge to its charge storage elements. Therefore, prior to a program operation, existing charge in charge storage element of a memory cell must be removed (or erased). A non-volatile memory such as EEPROM is referred to as a "Flash" EEPROM when an entire array of cells **200**, or significant groups of cells of the array, is electrically erased together (i.e., in a flash). Once erased, the group of cells can then be reprogrammed. The group of cells erasable together may consist of one or more addressable erase unit **300**. The erase unit or block **300** typically stores one or more pages of data, the page being a minimum unit of programming and reading, although more than one page may be programmed or read in a single operation. Each page typically stores one or more sectors of data, the size of the sector being defined by the host system. An example is a sector of 512 bytes of user data, following a standard established with magnetic disk drives, plus some number of bytes of overhead information about the user data and/or the block in with it is stored.

In the example shown in FIG. **6**, individual memory cells in the memory array **200** are accessible by word lines **42** such as WL**0**-WLy and bit lines **36** such as BL**0**-BLx. The memory is organized into erase blocks, such as erase blocks **0**, **1**, . . . m. Referring also to FIGS. **5**A and **5**B, if the NAND string **50** contains 16 memory cells, then the first bank of NAND strings in the array will be accessible by select lines **44** and word lines **42** such as WL**0** to WL**15**. The erase block **0** is organized to have all the memory cells of the first bank of NAND strings erased together. In another memory architecture, more than one bank of NAND strings may be erased together.

Examples of Binary (SLC) and Multi-State (MLC) Memory Partitioning

As described earlier, an example of nonvolatile memory is formed from an array of field-effect transistors, each having a charge storage layer between its channel region and its control gate. The charge storage layer or unit can store a range of charges, giving rise to a range of threshold voltages for each field-effect transistor. The range of possible threshold voltages spans a threshold window. When the threshold window is partitioned into multiple sub-ranges or zones of threshold voltages, each resolvable zone is used to represent a different memory states for a memory cell. The multiple memory states can be coded by one or more binary bits.

FIG. **7** illustrates a binary memory having a population of cells with each cell being in one of two possible states. Each memory cell has its threshold window partitioned by a single demarcation level into two distinct zones. As shown in FIG. **7**(**0**), during read, a read demarcation level rV_1, between a lower zone and an upper zone, is used to determine to which zone the threshold level of the cell lies. The cell is in an "erased" state if its threshold is located in the lower zone and is in a "programmed" state if its threshold is located in the upper zone. FIG. **7**(**1**) illustrates the memory initially has all its cells in the "erased" state. FIG. **7**(**2**) illustrates some of cells being programmed to the "programmed" state. A 1-bit or binary code is used to code the memory states. For example, the bit value "1" represents the "erased" state and "0" represents the "programmed" state. Typically programming is performed by application of one or more programming voltage pulse. After each pulse, the cell is sensed to verify if the threshold has moved beyond a verify demarcation level vV_1. A memory with such memory cell partitioning is referred to as "binary" memory or Single-level Cell ("SLC") memory. It will be seen that a binary or SLC memory operates with a wide margin of error as the entire threshold window is only occupied by two zones.

FIG. **8** illustrates a multi-state memory having a population of cells with each cell being in one of eight possible states. Each memory cell has its threshold window partitioned by at least seven demarcation levels into eight distinct zones. As shown in FIG. **8**(**0**), during read, read demarcation levels rV_1 to rV_7 are used to determine to which zone the threshold level of the cell lies. The cell is in an "erased" state if its threshold is located in the lowest zone and is in one of multiple "programmed" states if its threshold is located in the upper zones. FIG. **8**(**1**) illustrates the memory initially has all its cells in the "erased" state. FIG. **8**(**2**) illustrates some of cells being programmed to the "programmed" state. A 3-bit code having lower, middle and upper bits can be used to represent each of the eight memory states. For example, the "0", "1", "2", "3", "4", "5", "6" and "7" states are respectively represented by "111", "011", "001", "101', "100", "000", "010" and '110". Typically programming is performed by application of one or more programming voltage pulses. After each pulse, the cell is sensed to verify if the threshold has moved beyond a reference which is one of verify demarcation levels vV_1. to vV_7. A memory with such memory cell partitioning is referred to as "multi-state" memory or Multi-level Cell ("MLC") memory.

Similarly, a memory storing 4-bit code will have lower, first middle, second middle and upper bits, representing each of the sixteen states. The threshold window will be demarcated by at least 15 demarcation levels into sixteen distinct zones.

As the memory's finite threshold window is partitioned into more regions, the resolution for programming and reading will necessarily become finer. Thus, a multi-state or MLC memory necessarily operates with a narrower margin of error compared to that of a memory with less partitioned zones. In other words, the error rate increases with the number of bits stored in each cell. In general, error rate increases with the number of partitioned zones in the threshold window.

Correction by Error Correction Code ("ECC")

Flash memory is prone to errors. To ensure error-free data, an error correction code ("ECC") is implemented to correct errors.

FIG. **9** illustrates schematically a data page containing an ECC field. As described in connection with FIG. **4** and FIG. **6**A, a physical page of memory cells is programmed and read in parallel by virtue of a corresponding page of sense modules operating in parallel. When each memory cell stores multiple bits of data, there will be multiple data pages associated with each physical page. The data page **70'** comprises a user portion **72'** and a system portion **74'**. The user portion **72'** is for storage of user data. The system portion **74'** is generally used by the memory system for storage of system data. Included in the system data is an ECC. The ECC is computed for the data page. Typically, the ECC is computed by the ECC processor **62** in the controller **102** (see FIG. **1**.)

As data is received from a host, a page of data is staged in the controller **102** and its ECC **76'** is computed by the ECC processor **62**. The data page incorporating the ECC is then written to the memory array **200**. Typically, when the data

page is read, the data page is latched in the data latches **430** and shifted out of the I/O circuits **440** to the controller **102**. At the controller **102**, the data page's existing ECC is compared to a second version of the ECC computed on the read data. The ECC typically includes an error detection code ("EDC") for rapid detection of any error in the data page. If the EDC indicates the existence of any error in the read data page, the ECC is invoked to correct erroneous bits in the read data page.

The ECC can be designed to correct any number of error bits. The more bits it has to correct, the more complex and computationally intensive will the ECC be. For quality assurance, conventional ECC is designed based on the expected worst case cell error rate ("CER") at the end of life ("EOL") of the memory device. Thus, they have to correct a maximum number of error bits up to the far tail end of a statistical error population.

FIG. **10**A shows a normal distribution of error rate with the percentage of the population in various ranges of standard deviations σ. For example, only 2.1% of the population lies within the range from 2σ to 3σ. Only 0.1% of the population lies within the range from 3σ to 4σ.

FIG. **10**B illustrate the distribution of FIG. **10**A in a table format. It can be seen that only E-09 or one in one billion of the population lies beyond 6σ. The last column in the table shows the estimated error rates for an example memory device in the worst case. For example, 5% of the population will have 1 error bit, 0.135% of the population will have 4 error bits and 1 in 1 billion of the population will have 42 error bits.

Consider a sample of 125 memory cards. Each card has a capacity of 16 GB with data pages of 2 KB each. This amounts to a population of one billion pages of 2 KB each. To ensure not a single page of the sample of 125 memory cards will have an error at the end of life of the card, an ECC capable of correcting up to 42 bits will be needed.

Errors During the Life Time of Memory

As described above, an ECC is typically designed to correct for any errors expected during the useful life of the memory. The errors come from a number of sources.

FIG. **11** is a table listing the main sources of errors for a flash memory. FIG. **11**(A) shows a first source of error from post write $E_{PW}(N_{CYC})$ which is bit errors that are present after the page is written. In flash memory, "programming" refers to the process of increasing the threshold of a cell from an erased state. The term will be used interchangeable with "writing". The error rate increases with N_{CYC} the number of program-erase cycling. After data has been written to a cell, in spite of passing the verify operation, the data could still be erroneous for two causes.

The first cause of post write error is due to over-programming not detected by the verify operation. Over-programming that can happen when a number of the memory cells are to be programmed at the same time. This is because the characteristics of each memory cell are different due to minor variations in the structure and operation of the semi-conductor devices which comprise the memory cells; therefore, variations in the programming speed of different cells will typically occur. This results in memory cells that become programmed faster than others and the possibility that some memory cells will be programmed to a different state than intended. Faster programming of multiple memory cells can result in over-shooting desired threshold voltage level ranges, producing errors in the data being stored.

Typically, when data is being programmed, the program-verify process for the device will check if the programmed threshold voltage of the memory cell is above than a reference level demarcating the current state from the adjacent less programmed state. However, the program-verify does not know how much above the reference level is the programmed threshold voltage. Thus, devices typically do not guarantee an upper limit on the threshold voltage. Some devices do check to see if a soft programming process (described below) raised the threshold voltage too high; however, these devices do not check to see if a regular programming process raised the threshold voltage too high. Thus, over programming which raises the threshold voltage beyond the range for the desired state can occur without being noticed. Over programming can cause the memory cell to overshoot to the next programmed state and thus storing incorrect data. This error will be detected during subsequent read operations, in which the programmed threshold of a cell is typically checked relative to both a lower and an upper limit demarcating a threshold range for a given memory state. More information about over programming can be found in U.S. Pat. Nos. 5,321,699; 5,386,422; 5,469,444; 5,602,789; 6,134,140; 6,914,823; and 6,917,542.

The second cause of post write error is in the apparent shifts in the stored charge levels due to field coupling between storage elements. The degree of this coupling is necessarily increasing as the sizes of memory cell arrays are being decreased, which is occurring as the result of improvements of integrated circuit manufacturing techniques. The problem occurs most pronouncedly between two groups of adjacent cells that have been programmed at different times. One group of cells is programmed to add a level of charge to their storage elements that corresponds to one set of data. After the second group of cells is programmed with a second set of data, the charge levels read from the storage elements of the first group of cells often appear to be different than programmed because of the effect of the charge on the second group of storage elements being capacitively coupled with the first. In particular, when sensed the memory cell will appear to have a higher threshold level (or more programmed) than when it is less perturbed. This is also known as the Yupin effect, and is described in U.S. Pat. No. 5,867,429, which patent is incorporated herein in their entirety by this reference. This patent describes either physically isolating the two groups of storage elements from each other, or taking into account the effect of the charge on the second group of storage elements when reading that of the first group.

FIG. **11**(B) shows a second source of error $E_{DR}(T, N_{CYC})$ which is bit errors due to data retention at EOL. The error rate increases with temperature T and N_{CYC} the number of program-erase cycling. The data error is due to the history of the device. It typically is related to a data retention problem, which depends on the memory device exposure to the environment, e.g., temperature. Over time, the actual stored charge levels may leak away slowly, causing the programmed thresholds to decrease.

As the number of states stored in each memory cell increases, the tolerance of any shifts in the programmed charge level on the storage elements decreases. Since the ranges of charge designated for each storage state necessarily be made narrower and placed closer together as the number of states stored on each memory cell storage element increases, the programming must be performed with an increased degree of precision and the extent of any post-programming shifts in the stored charge levels that can be tolerated, either actual or apparent shifts, is reduced. Actual disturbs to the charge stored in one cell can be created when programming and reading that cell, and when reading, programming and erasing other cells that have some degree of electrical coupling with the that cell, such as those in the same column or row, and those sharing a line or node.

FIG. **11**(C) shows a third source of error $E_{RD}(N_R, N_{CYC})$ which are bit errors due to read disturb. The error rate increases with the number of reads and N_{CYC} the number of program-erase cycling.

An important consideration for flash memory is that it has an endurance problem as it ages with use. When a cell is repeatedly programmed and erased, charges are shuttled in and out of the floating gate **20** (see FIG. **2**) by tunneling across a dielectric. Each time some charges may become trapped in the dielectric and will modify the threshold of the cell. The number of program-erase cycles a cell has experienced is measured by a cycle count N_{CYC} (also known as "hot count'). Though repeated cycling, the value of N_{CYC} increases for a given erase block, causing the threshold window for the cells in the block to narrow progressively. Thus, the effect program-erase cycling will significantly impact all the sources of error listed in FIG. **11**.

FIG. **12** is a table showing estimated total errors for an example memory device at the beginning and end of its life. FIG. **12**(A) shows the total errors from the three sources listed in FIG. **11**(A) to FIG. **11**(C) to be $E_{TOT}(N_{CYC}, N_R)=E_{PW}(N_{CYC})+E_{DR}(T, N_{CYC})+E_{RD}(N_R, N_{CYC})$.

FIG. **12**(B) shows an estimated E_{TOT} when the memory is relatively fresh (low N_{CYC}) but has been baked at 85° C. for 5 years and has been read 10^6 times. The estimates for the various component errors are: $E_{PW}(1)\sim3$, $E_{DR}(85°\ C., 1)\sim2$, and $E_{RD}(1M, 1)\sim0$. These yield a total estimated error $E_{TOT}(1, 1M)=3+2+0=5$ bits.

FIG. **12**(C) shows an estimated E_{TOT} when the memory is near the end of life of the device ("EOL"). It is characterized by a high program-erase cycling (N_{CYC}=10K) with other parameters similar to that of FIG. **12**(B). The estimates for the various component errors are: $E_{PW}(10K)\sim10$, $E_{DR}(85°\ C., 10K)\sim10$, and $E_{RD}(1M, 10K)\sim1$. These yield a total estimated error $E_{TOT}(10K, 1M)=10+10+1=21$ bits.

Of the three sources of error described in FIG. **11** and FIG. **12**, generally the error due to read disturb E_{RD} is not as significant as error due to write E_{PW} and error due to data retention E_{DR}. Data retention errors can be alleviated by periodically refreshing the threshold levels of the cells in a "read scrub" operation.

To correct for the various errors that may arise in the memory, especially the error arising after write, an EEC (described earlier in connection FIG. **9**) is employed. However, using ECC to correct errors will consume processing time and, the more bits it has to correct, the more computational time is required. The memory performance will be degraded by employing a strong ECC able to correct a large number of error bit. Additional dedicated hardware may be implemented to perform the ECC in a reasonable amount of time. Such dedicated hardware can take up a considerable amount of space on the controller ASIC chip.

FIG. **13** is a table illustrating that a conventional ECC must be designed to correct the worst-case total error E_{TOT}. That will be a device at the end of life with high program-erase cycle count and data retention specification. For the example given in FIG. **12**(C), the ECC must be capable of correcting at least 21 error bits.

Adaptively Rewrite Data from a Higher Density Memory Portion to a Lower Error Rate Memory Portion to Control Error Rate

According to a general aspect of the invention, a flash memory having an array of memory cells is configured with a first portion and a second portion. The second portion stores data at higher density but operates with a smaller margin of errors compared to the first portion. Data is written to the second portion for efficient storage. Afterwards, the data is read back to check for excessive error bits. If the error bits exceeded a predetermined amount, the data is rewritten to the less error-prone first portion. This places a limit on the maximum number of error bits arising from writing data to the memory. In a statistical distribution of error rates, the limit represents a limit on the number standard derivations of the distribution so that the far tail-end of the distribution (with higher error rates) can be ignored. This allows a smaller and more efficient error correction code ("ECC") to be designed for correcting a smaller number of errors bits, thereby improving the performance and reducing the cost of the memory.

FIG. **14**A illustrates a memory array being partitioned into two portions according to a preferred embodiment of the invention. The array of memory cells **200** is partitioned into a first portion **410** and a second portion **420**. The second portion **420** has the memory cells configured as high density storage with each cell storing multiple bits of data. The first portion **410** has the memory cells configured as lower density storage with each cell storing less number of bits than that of the second portion. For example, a memory cell in the first portion is configured to store 1 bit of data as compared to 3 bits of data in the second portion. In view of the discussion earlier, the first portion will operate with a much wider margin of error compared to that of the second portion. Thus, memory operations in the first portion will have less error than that in the second portion.

U.S. Pat. No. 6,456,528, entitled "Selective Operation of a Multi-state Non-volatile Memory System in a Binary Mode", discloses a flash non-volatile memory having memory cells normally operating in more than two states but with selected memory cells operating in only two-states in order to provide an increased margin during two-state operation. This allows faster programming and a longer operational life of the memory cells being operated in two states when it is more desirable to have these advantages than the increased density of data storage that multi-state operation provides. The entire disclosure of U.S. Pat. No. 6,456,528 is incorporated herein by reference.

When a page of incoming data is to be written to the memory array **200**, it is preferably stored in the high density second portion for the sake of efficiency and high capacity. Thus a first copy of the data page is written to the second portion.

Later, the first copy of the data page is read back in a "post write read" to determine if there are any errors. This is accomplished either by comparison with the original copy which may be cached or by checking the EDC portion of the ECC.

Determination is made whether the number of error bits in the read copy exceeded a predetermined amount. If the number of error bits does not exceed the predetermined amount, the first copy is regarded stored in the second portion is deemed valid. Subsequent read of the data page will be from the first copy in second portion and any errors will be corrected by ECC at the controller.

As explained earlier in connection with FIG. **11**, the verify process during programming only checks for under-programming and not over-programming. Thus, error may still exist after the data page has been program-verified. It will take a read operation relative to all the demarcation levels (see FIG. **7** and FIG. **8**) to detect any error in the data page. Furthermore, the Yupin effect of subsequent programming of neighboring cells could perturb the data page in question and shift the apparent sensed results. Thus, the read back should at least be after the programming of all neighboring cells that could have significant Yupin effect on the current data page. In

another embodiment, the read back is after all the cells in the block containing the data page in question are done programming.

"Post write read" is also disclosed in U.S. Pat. Nos. 6,914,823, 6,917,542 and 7,009,889, their entire disclosures are incorporated herein by reference.

FIG. **14**B illustrates a rewrite of a second copy of the data page into the first portion of the memory array of FIG. **14**A. After the post-write read detects the number of error bits in the data page has exceeded the predetermined amount, a second copy of the data page is rewritten to the first portion. The second copy is of the original data which may be cached or in another embodiment, by retrieving the first copy and correcting the error bits with the ECC.

After the second copy has been written to the first portion, it will replace the first copy in the second portion as the valid copy. The first copy will become obsolete and a directory in a block management system embodied in the firmware of the controller (see FIG. **1**) will be updated to direct subsequent access to the second copy.

In one preferred embodiment, the first portion has each memory cell storing one bit of data and the second portion has each memory cell storing more than one bit of data.

FIG. **15** is a flow diagram illustrating the process of post-write read and adaptive rewrite according to the embodiment described in FIG. **14**A and FIG. **14**B.

STEP **500**: Configuring the memory into first and second portions, the first portion having memory cells operating with a margin of error larger than that of the second portion.

STEP **510**: Programming a first copy of a group of input data in the second portion.

STEP **520**: Reading the first copy from the second portion to check for error after a predefined time.

STEP **530**: Does the error exceed a predetermined number of error bits? If so, proceed to STEP **540**. Otherwise proceed to STEP **550**.

STEP **540**: Programming a second copy of the group of input data in the first portion.

STEP **550**: Identifying the last written copy as valid data for subsequent read.

STEP **560**: The group of input data is done storing in the nonvolatile memory.

In an alternative embodiment, the first portion serves as a cache for incoming data, so a cache copy of the input data is programmed into the cache. Then a first copy of data is programmed into the second portion.

If the post-write read has not detected an excessive amount of error in the first copy, the first copy will be deemed valid and subsequent read will be directed to access the first copy.

On the other hand, if the post-write read has detected an excessive amount of error in the first copy, the cached copy in the first portion will replace the first copy in the second portion as valid data. The first copy will become obsolete and a directory in a block management system embodied in the firmware of the controller (see FIG. **1**) will be update to direct subsequent access to the cached copy.

U.S. Pat. No. 5,930,167, entitled "Multi-state Non-volatile Flash Memory Capable of Being its Own Two State Write Cache", discloses a flash memory array having two portions. A first portion is configured to store one bit per cell and a second portion is configured to store more than one bit per cell. The first portion acts as a low-density write cache. Incoming data is initially cached in the first portion. At a later time, in the background, the cached data is transferred to the second portion with higher storage density. The entire disclosure of U.S. Pat. No. 5,930,167 is incorporated herein by reference.

In the preferred embodiment, the first portion is further provided with a first section and a second section. The incoming data is cached in the first section of the first portion and a first copy of the data is written to the second portion. Afterwards, the first copy in the second portion is read back to check for excessive error bits. If the error bits exceeded a predetermined amount, a second copy of the in coming data is written to the second section of the first portion.

FIG. **16**A illustrates a memory array being partitioned into two portions and the first portion further provided with a cache section and rewrite section, according to a preferred embodiment of the invention. As in FIG. **14**A, the array of memory cells **200** is partitioned into a first portion **410** and a second portion **420**. The second portion **420** has the memory cells configured as high density storage with each cell storing multiple bits of data. The first portion **410** has the memory cells configured as lower density storage with each cell storing less number of bits than that of the second portion. The first portion therefore operates with a wider margin of error than that of the second portion.

The first portion **410** is further provided with a first section **411** for caching incoming data and a second section **412** for storing rewrites from the second portion.

When a page of incoming data is to be written to the memory array **200**, a cached copy is cached in the first section **411** of the first portion **410**. A first copy is preferably stored in the high density second portion for the sake of efficiency and high capacity. Thus a first copy of the data page is written to the second portion.

According to another preferred embodiment, the memory array is provided with a set of data latches on an integrated circuit chip, the checking of the error bits in the first copy is accomplished by loading the first copy and the cached copy into the set of data latches and making a comparison at the set of data latches.

By not making the comparison at the controller, the data does not have to be toggled out to the controller, much time can be saved. FIG. **1** shows the data latches **430**, which is on-chip, for the data comparison to take place.

FIG. **16**B illustrates a page compare technique according a preferred embodiment of the post-write read. The first copy of the data page in the second portion is read back in a "post write read" to determine if there are any errors. This is accomplished by comparison with the cached copy.

If the number of error bits does not exceed the predetermined amount, the first copy stored in the second portion is deemed to be valid. The cached copy will become obsolete and a directory in a block management system embodied in the firmware of the controller (see FIG. **1**) will be updated to direct subsequent access to the first copy. Subsequent read of the data page will be from the first copy in the second portion and any errors will be corrected by ECC at the controller.

FIG. **16**C illustrates a rewrite to the first portion after a post-write read has determined an excessive amount of error in the data page in the second portion. After the post-write read detects the number of error bits in the data page of the first copy has exceeded the predetermined amount, a second copy of the data page is rewritten to the second section **412** of the first portion **410**. The second copy is taken from the cached copy.

After the second copy has been written to the second section **412** of the first portion, it will replace the first copy in the second portion. The first copy and the cached copy will become obsolete and a directory in a block management system embodied in the firmware of the controller (see FIG. **1**) will be updated to direct subsequent access to the second copy.

FIG. **17** is a flow diagram illustrating the process of post-write read and adaptive rewrite according to the embodiment described in FIG. **16**A to FIG. **16**C.

STEP **600**: Configuring the memory into first and second portions, the first portion having memory cells operating with a margin of error larger than that of the second portion.

STEP **602**: Programming a cached copy of a group of input data in a first section of the first portion.

STEP **610**: Programming a first copy of the group of input data in the second portion.

STEP **620**: Reading the first copy from the second portion to check for error after a predefined time.

STEP **630**: Does the error exceed a predetermined number of error bits? If so, proceed to STEP **632**. Otherwise proceed to STEP **650**.

STEP **632**: Reading the cached copy of the group of input data from the first section of the first portion.

STEP **642**: Programming the cached copy as a second copy of the group of input data in a second section of the first portion.

STEP **650**: Identifying the last written copy as valid data for subsequent read.

STEP **660**: The group of input data is done storing in the nonvolatile memory.

The foregoing detailed description of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed. Many modifications and variations are possible in light of the above teaching. The described embodiments were chosen in order to best explain the principles of the invention and its practical application, to thereby enable others skilled in the art to best utilize the invention in various embodiments and with various modifications as are suited to the particular use contemplated. It is intended that the scope of the invention be defined by the claims appended hereto.

Enhanced Post-Write-Read Error Management

In another aspect of the invention, an enhanced post-write read error management is implemented. The post-write read is not enabled at the beginning of life of a memory device. The error rate of the memory device at the beginning of life is very low and there is no need to operate the post-write read. This avoids wasting time to do post-write read. As the memory device ages through use, the enhanced post-write read and error management of the invention is enabled at a predetermined age of the device.

In a preferred embodiment, the age of the memory device is determined by a hot count maintained with each erase block of memory cells. The hot count tracks the endurance or the number of times the erase block has been cycled through erase and program operations. Whenever a hot count of an erase block passes a predetermined hot count threshold, the enhanced post-write-read error management will commence and operate until the end of life of the memory device.

FIG. **18** illustrates a memory organized into erase blocks. As described in connection with FIG. **6** earlier, each erase block is a group of memory cells that are erased together. Also described earlier is when a cell is repeatedly programmed and erased, charges are shuttled in and out of the floating gate **20** (see FIG. **2**) by tunneling across a dielectric. Each time some charges may become trapped in the dielectric and will modify the threshold of the cell. The number of program-erase cycles a cell has experienced is measured by a cycle count N_{CYC} (also known as "hot count'). Though repeated cycling, the value of N_{CYC} increases for a given erase block, and the threshold window for the cells in the block narrows progressively. FIG. **18** illustrates a preferred embodiment in which a hot count N_{CYC}(m) **302** is maintained in each erase block (m). Since the programmable unit is a page, the hot count for each block can be store in the system data area of the data page **70'** illustrated in FIG. **9**. Alternatively, the hot counts may be stored in a master list in the memory. Every time a block is erased, its hot count is incremented by one.

FIG. **19** is a flow diagram illustrating the error management being enabled when the memory device has aged to a predetermined degree as determined by a hot count.

STEP **700**: Providing a non-volatile memory organized into erase blocks of memory cells, wherein the memory cells of each erase block are erased together and age with the number of erase/program cycling of each block.

STEP **710**: Providing an error management for correcting errors associated with an aging memory device. In the preferred embodiment, the error management is the post-write-read error management described earlier.

STEP **720**: Tracking the age of each block by maintaining a hot count that records the number of erase/program cycling each block has undergone.

STEP **730**: Is the Hot Count of a memory block>a predetermined hot count threshold? In the preferred embodiment, the predetermined hot count threshold is given by a parameter Hot_count_threshold_EPWR in a file system configuration file stored in the memory (see FIG. **21**.) If greater than, go to STEP **740**, otherwise go to STEP **750**.

STEP **740**: Enable the error management for the rest of the life of the memory.

STEP **750**: Do not enable the error management yet.

In a preferred embodiment of yet another aspect of the invention, the high density storage portion of the memory (D**3**) has each memory storing 3 bits of data. The less error-prone, low density storage portion of the memory (D**1**) has each memory cell storing 1 bit of data. Input data is first staged in D**1** and subsequently folded into D**3**. When the enhanced post-write-read error management is enabled, a current, filled block in D**3** is read back; and if the error rate exceeds a predetermined threshold, the current D**3** block is rejected and a retry takes place with data being refolded into a new D**3** block. The new D**3** block is again read back and checked for excessive error rate. If the new D**3** block passes, then it has good data and the original data in D**1** is made obsolete. If the new D**3** block again shows excessive error rate, the new D**3** block is again discarded. If the excessive error rate persists after a predetermined number of retries, no further retry is attempted and the D**1** to D**3** folding operation is abandoned with the original data kept at D**1**. At this point the memory device is deemed too old for further programming operations and is made read-only to preserve the integrity of the existing data stored in the memory device.

FIGS. **20**A-**20**C illustrate various examples of implementing the post-write-read error management in a memory configured with D**1** and D**3** portions. A memory configured with D**1** and D**3** portion is also disclosed in U.S. application Ser. No. 12/642,584, entitled "MAINTAINING UPDATES OF MULTI-LEVEL NON-VOLATILE MEMORY IN BINARY NON-VOLATILE MEMORY" by Gorobets et al, filed on Dec. 18, 2009; the entire disclosure of which is incorporated herein by reference.

FIG. **20**A illustrates a memory array being partitioned into two portions according to a preferred embodiment of the invention. The array of memory cells **200** (see FIG. **1**) is partitioned into a first portion **410** and a second portion **420**. The second portion **420** has the memory cells configured as high density storage with each cell storing multiple bits of data. The first portion **410** has the memory cells configured as lower density storage with each cell storing less number of

bits than that of the second portion. For example, a memory cell in the first portion is configured to store 1 bit of data as compared to 3 bits of data in the second portion. The first portion storing 1 bit of data per cell will also be referred as D**1** and the second portion storing 3 bit of data per cell as D**3**. In view of the discussion earlier, the first portion will operate with a much wider margin of error compared to that of the second portion. Thus, memory operations in the first portion will have less error than that in the second portion.

In one embodiment, the first portion **410** or D**1** is further partitioned into a first section **411** and a second section **412**.

In Step (1), during a host write, input data is either first cached in the first section **411** or written directly to the second section **412**. If the input data is fragmented, it is first cached in the first section. If the input data is a substantial run of sequential data, it is written page by page directly into the second section **412**.

In Step (2), in any case, the input data eventually ends up in the second section **412** where the written pages are staged into virtual D**1** blocks, such as blocks m.**1**, m.**2** and m.**3**. In a scheme where each block contains data from a well defined group of logical addresses, a virtual block may not correspond to a physical block but still have the group of logical addresses distributed over several physical D**1** blocks.

In Step (3), as data is being written page by page into D**1**, when a triplet of binary pages is in D**1**, it can be copied to a single 3-bit page in D**3** in what is also referred to as folding from D**1** to D**3**.

By implementing the enhanced post-write-read error management ("EPWR"), at some point which the lifetime of the memory the post-write-read error management will commence.

In Step (4), a D**3** block m is complete after the entire pages of the virtual D**1** blocks m.**1**, m.**2** and m.**3** have been folded into it. Thereafter it can be processed by the EPWR where the data in the D**3** block is read back and checked for ECC errors. If the number of ECC errors is less than a predetermined threshold as such given by a parameter E_pw_check set in the File system configuration file, then the data in the D**3** block is deemed valid. The corresponding D**1** pages can then be safely replaced and retired.

FIG. **20**B illustrates another example in which the D**3** block of FIG. **20**A fails a post-write-read test. Step (1) to Step (3) are the same as that of FIG. **20**A.

In Step (4'), when the data in the D**3** block is read back, the number of ECC error is found to be greater than E_pw_check. This means the data in D**3** is marginal at best and can not be used.

In Step (5), in the event of the existing D**3** block failing the post-write-read test, the EPWR prescribes a retry by folding the data into a new D**3** block.

In Step (6), the data in the new D**3** block is subjected to another post-write-read test. If it passes the test, the data in the new D**3** block is deemed valid. The corresponding D**1** pages can then be safely replaced and retired.

FIG. **20**C illustrates another example in which the new D**3** block of FIG. **20**B fails the post-write read test again. Step (1) to Step (5) are the same as that of FIG. **20**B.

In Step (6'), when the data in the new D**3** block is read back, the number of ECC errors is found to be greater than E_pw_check. This means the data in the retried D**3** block is still not good and can not be used.

The EPWR process can prescribe further retry to another D**3** block. The number of retries is set by a parameter, EPWR_retries in the file system configuration file. For example, if EPWR_retries is 1, then the process will end after the new block fails the test.

In that event, in Step (7), the new D**3** block can not be used and the file system will direct access to corresponding data that reside in D**1** instead.

FIG. **21** is a table illustrating example parameters associated with the enhanced post-write-read error management. The table is preferably maintained in the file system configuration file stored in memory.

E_pw_check—a variable set in File System Configuration File to specify at what # of ECC bits level, a D**3** block is consider high risk and restart of D**1** to D**3** folding to a new D**3** block is required.

ECC_threshold_SLC—a variable is needed in File System Configuration File for maintaining SLC threshold to compare against in order to make a decision to continue with EPWR or not.

EPWR_enable_flag—controlled in File System Configuration File. 0=not set (Default); 1=set when EPWR is enabled.

Hot_count_enable_flag—0=not enabled; 1=enabled.

Hot_count_threshold_EPWR—a variable set in File System Configuration File to specify at what hot count level, EPWR is needed. If hot count of all D**3** blocks is<hot count threshold, even EPWR enable flag is on, EPWR process is not triggered.

EPWR_verify_page_budget—a variable set in File System Configuration File to specify how many pages can be read during 1 phase of EPWR.

EPWR_retries—a variable in File System Configuration File to limit number of retry attempts.

D**3**_Block_max_retries—a variable in File System Configuration File to limit the total number of retry attempts on a D**3** block over lifetime.

FIG. **22**A is a flow diagram illustrating a preferred implementation of the EPWR error management as applied to a memory having D**1** to D**3** folding.

STEP **800**: Start.

STEP **810**: D**1** to D**3** Folding in which data from three binary data pages of D**1** is programmed into one tertiary page of D**3** as described in connection with FIG. **20**A.

STEP **812**: Is a D**3** block completely filled? If completely filled, proceed to STEP **820**, otherwise return to STEP **810**.

STEP **820**: Is enhanced post-write-read error management ("EPWR") enabled? More details of a device-age-dependent enablement is given in FIG. **22**B. If EPWR is enabled, process EPWR in STEP **830**. If not, the integrity of the D**3** block written is unknown, but optimistically assumed to be good. Proceed to STEP **850**.

STEP **830**: Process EPWR. A more detailed implementation of EPWR is given in FIG. **22**C.

STEP **840**: At a higher level, essentially, the EPWR performs a post-write-read of the D**3** block and test of the rate of ECC errors. If the errors does not exceed E_pw_check (see FIG. **21**), the D**3** block is good. Proceed to STEP **850**. Otherwise, the data in the D**3** block cannot be used and a retry of folding the D**1** data to a new D**3** block is considered. Proceed to STEP **860**.

STEP **850**: The D**3** block is deemed good so the original copy of data in D**1** can be made obsolete and retired.

STEP **860**: Decide whether to retry on a new D**3** block based on a number considerations detailed in FIG. **22**C. If not permitted to retry, proceed to STEP **870**. Otherwise proceed to STEP **862** (shown in FIG. **22**C).

STEP **862**: The D**1** to D**3** folding is repeated on a new D**3** block. Return to process another block.

STEP **870**: The data in the D**3** block is deemed bad, so data must be accessed from original copy in D**1**.

STEP **872**: Since this step is reached after a number of unsuccessful retries in attempting to rewrite the D**3** block, the memory is deemed near end of it its life. It is put into a read-only state to prevent any data corruption due to programming operations. Proceed to STEP **890**.

STEP **890**: Done.

FIG. **22**B illustrates in more detail the device-age-dependent enablement feature of the enhanced post-write-read error management. The STEP **820** in FIG. **22**A is shown in FIG. **22**B to further include the following:

STEP **822**: Check if the EPWR_enable_flag (see FIG. **21**) is enabled. If not enabled, EPWR is not been implemented at all. Proceed by default to STEP **850** where the D**3** block is deemed good. If enabled, proceed to STEP **824** to control if EPWR should commence after some aging of the memory device.

STEP **824**: Check if the Hot_count_enable_flag (see FIG. **21**) is enabled. If not enabled, EPWR is implemented from the beginning of life of the memory device. Proceed directly to STEP **830** to process EPWR. If the flag is enabled, proceed to STEP **826** which controls when EPWR should commence.

STEP **826**: Check if any one of the D**3** blocks has a hot count that exceeds the value in Hot_count-threshold_EPWR. If not exceeded the memory device is still young and not prone to excessive errors, proceed to STEP **850** and EPWR is essentially on hold. If the hot count has exceeded the threshold, the memory device has attained an age when errors becomes significant and will benefit from the EPWR process. Proceed to STEP **830** to process EPWR.

FIG. **22**C illustrates in more detail a preferred implementation of the enhanced post-write-read error management. The STEP **830** in FIG. **22**A is shown in FIG. **22**C to further include the following:

STEP **832**: Check if there is process time available for doing post-write-read of the D**3** block and possible retries. The available time is preferably taken from unused time during the execution of a host command in the foreground. If necessary the process can be broken down to smaller chunks so as to better utilize the spare time during each host command. If there is available time to start the process, proceed to STEP **834**, otherwise, proceed to STEP **838**.

STEP **834**: Start the process or if the process has already been started but interrupted in the interim, continue the process.

STEP **836**: Read and transfer a page of data from D**3** out to the controller for checking EDC (error detection code). Proceed to STEP **838**.

STEP **840**: The EPWR performs a post-write-read of the D**3** block and test of the rate of ECC errors. If the errors does not exceed E_pw_check (see FIG. **21**), the page being tested is in D**3** is good. Proceed to STEP **842**. If a page is tested to be bad, the data in the D**3** block cannot be used and a retry of folding the D**1** data to a new D**3** block is considered. Proceed to STEP **864**.

STEP **842**: Has all the pages in the D**3** block been tested? If not, proceed to STEP **844** to process the next page. If the whole block is tested to be good, proceed to STEP **850**.

STEP **844**: Select the next page in the D**3** block. Return to STEP **836**.

STEP **862**: Before a retry is attempted, check if the number of retries has already exceeded a set limit, EPWR_retries (see FIG. **21**.) If not, a retry is attempted by proceeding to STEP **866**. If the number of retries has exceeded the set limit, the memory device is deemed to be at its end of life and control proceeds to STEP **870**.

STEP **866**: Another consideration before attempting a retry is to check if the excessive errors are intrinsic to the data in D**1** and not due to programming errors from D**1** to D**3**. The D**1** data is first checked for excessive ECC errors. If the number of error exceeded a predetermined threshold, such as, ECC_threshold_SLC (see FIG. **21**), there is no point in a retry. Return to STEP **834** to process another D**3** block.

However, if an optional feature as described below is implemented, proceed to an optional STEP **868** instead. On the other hand if the D**1** data is good, proceed to attempt retry of another D**3** block in STEP **869**. In another embodiment, STEP **866** is performed before STEP **862**.

FIG. **22**C also illustrates optional features as indicated by boxes with broken lines. One option is illustrated by STEPs **864** and **865** to check if a block has been subjected too many retries over its lifetime. If so, the physical integrity of the block may be in question and it is best to retire the block so that it is not used again. When this option is implemented, the flow from a NO in STEP **862** will be routed to STEP **864**.

STEP **864**: Has the D**3** block experience retries more than a threshold as defined by the parameter Block_max-retires (see FIG. **21**). If so, proceed to STEP **865** to retire the block, otherwise proceed to STEP **866** for further rewrite decision.

STEP **865**: The D**3** block has be subjected to too many retries over its lifetime to be deemed robust. It is retired and taken out of circulation. Control then proceed directly to STEP **869** to rewrite the D**3** block.

The other option is that in the event the D**1** data is not very good, it is first corrected by ECC and restaged in D**1** before being folded to D**3**. When this option is implemented, the flow from a YES in STEP **866** will be routed to STEP **868** instead of STEP **834**.

STEP **868**: The problematic D**1** data is corrected by ECC and restaged in D**1**. Proceed to STEP **869**.

Accelerated Post-Write Read

Previous sections have described the techniques of actually reading the data back after they have been written (also referred to as "programmed"). This technique is called "PWR" (Post Write Read). According to one aspect of the invention described earlier, the PWR technique is enhanced and is referred to as "EPWR" (Enhanced Post Write Read). In this case, the PWR operation is only turned on when needed. For example, PWR is initiated only after the memory begins to develop more errors through use. This will alleviate some of the overheads associate with PWR.

According to another aspect of the invention, instead of post-write reading every memory cells to check what have been written, which could consume a lot of time and system resources, the post-write read is only performed on a small sample of memory cells representing a population of memory cells with a similar error rate. When the post-write read of the sample yields an error rate within a predetermined value, the population is assumed to pass the check. Otherwise, the data previously written on the population of cells are deemed to have too much error and are either rewritten again to a different location in the same area or to another area of the memory with intrinsic lower error rate.

As explained earlier, post-write read checking is different from the usual program verify that is part of programming operation. In programming a cell, it is subjected to pulse by pulse programming voltages. In between each pulse the cell's programmed threshold is compared to a reference read threshold. Once the cell's threshold is detected to be programmed passed the reference read threshold, the cell is locked out from further programming by a program inhibiting voltage applied to its bit line. Thus, program-verify only guarantee if the cell has been programmed pass a reference threshold but gives no indication of any over programming

that may have occurred. A read operation for MLC memory actually checks if the programmed threshold is between a pair of reference thresholds.

In MLC memory each cell stores more than one bit of data. For example in D**2** memory, each cell stores two bits of data. The threshold window supported by the cells is partitioned by a reference threshold into two halves. When the programmed threshold of a cell lies in a first half, it has one bit value, e.g., '1' and when in a second half, it has the other bit value, e.g., '0'. Similarly, in D**3** memory, each cell stores three bits of data and in D**4** memory, each cell stores four bits of data. In general, for a Dm memory, each cell stores m bits and the threshold window is partitioned into 2^m voltage bands by 2^m-1 reference thresholds. A coding scheme is used to assign each of the voltage bands with an m-bit code word.

Exemplary Preferred "LM" Coding for a 2-Bit or 4-State Memory

FIGS. **23**(**0**)-**23**(**3**) illustrate a logical page by page programming of a 4-state memory encoded with a preferred 2-bit logical code ("LM" code). The 2 code bits from each memory cell of a page form two logical pages with each page formed from one code bits contributed from every memory cells of the page. Programming can be performed logical-page by logical page with the lower page followed by the upper page. This code provides fault-tolerance and alleviates the BL-BL floating-gate coupling (Yupin) Effect.

FIG. **23**(**0**) illustrates the threshold voltage distributions of a 4-state memory array. The possible threshold voltages of each memory cell span a threshold window which is partitioned into four regions to demarcate four possible memory states, "Gr", "A", "B" and "C". "Gr" is a ground state, which is an erased state within a tightened distribution and "A", "B" and "C" are three progressively programmed states. During read, the four states are demarcated by three demarcation reference thresholds, D_A, D_B and D_C.

FIG. **23**(**3**) illustrates a preferred, 2-bit LM coding to represent the four possible memory states. Each of the memory states (viz., "Gr", "A", "B" and "C") is represented by a pair of "upper, lower" code bits, namely "11", "01", "00" and "10" respectively. The LM coding differs from the conventional Gray code in that the upper and lower bits are reversed for states "A" and "C". The "LM" code has been disclosed in U.S. Pat. No. 6,657,891 and is advantageous in reducing the field-effect coupling between adjacent floating gates by avoiding program operations that require a large change in charges. As will be seen in FIGS. **23**(**2**) and **23**(**3**), each programming operation results in moderate change of the charges in the charge storage unit as evident from the moderate change in the threshold voltages V_T.

The coding is designed such that the 2 code bits, "lower" and "upper" bits, may be programmed and read separately. When programming the lower bit, the threshold level of the cell either remains in the "erased" region or is moved to a "lower middle" region of the threshold window. When programming the upper bit, the threshold level of a cell in either of these two regions is further advanced to a slightly higher level in a "lower intermediate" region of the threshold window.

FIGS. **23**(**1**) and **23**(**2**) illustrate the lower page programming using the 2-bit LM code. The fault-tolerant LM code is designed to avoid any subsequent upper page programming to transit through any intermediate states. Thus, the first round, lower page programming has a cell remain in the "erased" or "Gr" state if the lower bit is "1" or programmed to a "lower intermediate" state if the lower bit is "0". Basically, the "Gr" or "ground" state is the "erased" state with a tightened distribution by having the deeply erased states programmed to within a well-defined range of threshold values. The "lower intermediate" states may have a broad distribution of threshold voltages that straddle between memory states "A" and "B". During programming, the "lower intermediate" state is verified relative to a coarse demarcation such as D_A.

FIGS. **23**(**2**) and **23**(**3**) illustrate the upper page programming using the 2-bit LM code. The upper page programming is performed on the basis of the first round, lower page programming. A given upper bit can represent different memory states depending on the value of the lower bit. In the second round of programming, if a cell is to have the upper bit as "1" while the lower bit is at "1", i.e. (1,1), there is no programming for that cell and it remains in "Gr". If the upper bit is "0" while the lower bit is at "1", i.e., (0,1), the cell is programmed from the "Gr" state to the "A" state. During programming to "A", the verifying is relative to the demarcation DV_A. On the other hand, if the cell is to have the upper bit as "0" while the lower bit is at "0", i.e., (0,0), the cell is programmed from the "lower intermediate" state to "B". The program verifying is relative to a demarcation DV_B. Similarly, if the cell is to have the upper bit as "1" while the lower page is at "0", i.e., (1,0), the cell will be programmed from the "lower intermediate" state to "C". The program verifying is relative to a demarcation DV_C. Since the upper page programming only involves programming to the next adjacent memory state from either the "Gr" state or the "lower intermediate" state, no large amount of charges is altered from one round to another. Also, the lower page programming from "Gr" to a rough "lower intermediate" state is designed to save time.

FIG. **24**A illustrates the read operation that is required to discern the lower bit of the 4-state memory encoded with the 2-bit LM code. The decoding will depend on whether the upper page has been programmed or not. If the upper page has been programmed, reading the lower page will require one read pass of readB relative to the demarcation threshold voltage D_B. On the other hand, if the upper page has not yet been programmed, the lower page would be programmed to the "intermediate" state (see FIG. **23**(**2**)), and readB would cause error. Rather, reading the lower page will require one read pass of readA relative to the demarcation threshold voltage D_A. In order to distinguish the two cases, a flag ("LM" flag) is written in the upper page (usually in an overhead or system area) when the upper page is being programmed During a read, it will first assume that the upper page has been programmed and therefore a readB operation will be performed. If the LM flag is read, then the assumption is correct and the read operation is done. On the other hand, if the first read did not yield a flag, it will indicate that the upper page has not been programmed and therefore the lower page would have to be read by a readA operation.

FIG. **24**B illustrates the read operation that is required to discern the upper bit of the 4-state memory encoded with the 2-bit LM code. As is clear from the figure, the upper page read will require a 2-pass read of readA and readC, respectively relative to the demarcation threshold voltages D_A and D_C. Similarly, the decoding of upper page can also be confused by the "intermediate" state if the upper page is not yet programmed Once again the LM flag will indicate whether the upper page has been programmed or not. If the upper page is not programmed, the read data will be reset to "1" indicating the upper page data is not programmed.

If the read is to scan through all sequence of the demarcated states as in a "full-sequence" read or "all-bit" read, the read is performed relative to the memory states "Gr", "A", "B" and "C" demarcated respectively by reference threshold voltages D_A, D_B and D_C. As all possible states are differentiated by the

full-sequence read, there is no need to check for any LM flag. In this mode of read, all bits are determined together.

Exemplary Preferred "LM" Coding for a 3-Bit or 8-State Memory

The example for the 2-bit LM code can be similarly extended to 3-bit or high number of bits.

FIGS. **25**(**0**)-**25**(**4**) illustrate the programming of an 8-state memory encoded with a preferred 3-bit logical code ("LM" code). The 3 bits from each memory cell of a page forms three logical pages and programming can be performed logical-page by logical page. This code is similar to the 2-bit LM coding described earlier and is an extension into 3 bits to encode eight possible memory states. FIG. **25**(**0**) illustrates the threshold voltage distributions of an 8-state memory array. The possible threshold voltages of each memory cell spans a threshold window which is partitioned into eight regions to demarcate eight possible memory states, "Gr", "A", "B", "C", "D", "E", "F" and "G". "Gr" is a ground state, which is an erased state within a tightened distribution and "A"-"G" are seven progressively programmed states. During read, the eight states are demarcated by seven demarcation reference thresholds, D_A-D_G.

FIG. **25**(**4**) illustrates a preferred, 3-bit LM coding to represent the eight possible memory states. Each of the eight memory states is represented by a triplet of "upper, middle, lower" bits, namely "111", "011", "001", "101", "100", "000", "010" and "110" respectively. As will be seen in FIGS. **25**(**1**) and **25**(**4**), each programming operation results in moderate change in the charges in the charge storage unit as evident from the moderate change in the threshold voltages V_T.

The coding is designed such that the 3 code bits, "lower", "middle" and "upper" bits, may be programmed and read separately. Thus, the first round, lower page programming has a cell remain in the "erased" or "Gr" state if the lower bit is "1" or programmed to a "lower intermediate" state if the lower bit is "0". Basically, the "Gr" or "ground" state is the "erased" state with a tightened distribution by having the deeply erased states programmed to within a narrow range of threshold values. The "lower intermediate" states may have a broad distribution of threshold voltages that straddling between memory states "B" and "D". During programming, the "lower intermediate" state can be verified relative to a coarse demarcation reference threshold level such as D_B. When programming the middle bit, the threshold level of a cell will start from one of the two regions resulted from the lower page programming and move to one of four possible regions. When programming the upper bit, the threshold level of a cell will start from one of the four possible regions resulted from the middle page programming and move to one of eight possible memory states.

In general a page of memory cells is being programmed in parallel, with each memory cell having 3 bits. Thus, the page of memory cells may be regarded as having 3 logical data pages with each logical data page contributed from one code bit of every cells of the page. Thus, a "lower bit" page is formed from the lower bit of every memory cells of the page, a "middle bit" page is formed from the middle bit of every cell and an "upper bit" page is formed from the upper bit of every cell of the page.

FIGS. **25**(**1**) and **25**(**2**) illustrate the lower page programming using the 3-bit LM code. The fault-tolerant LM code is designed to avoid any subsequent higher page programming to transit through any intermediate states. Thus, the first round, lower page programming has a cell remain in the "erased" or "Gr" state if the lower bit is "1", i.e. (x,x,1) or programmed to a "lower intermediate" state if the lower bit is "0", i.e., (x,x,0). Basically, the "Gr" or "ground" state is the "erased" state with a tightened distribution by having the deeply erased states programmed to within a well-defined range of threshold values. The "lower intermediate" states may have a broad distribution of threshold voltages that straddling between memory states "B" and "D". During programming, the "lower intermediate" state is verified relative to a demarcation such as D_B.

FIGS. **25**(**2**) and **25**(**3**) illustrate the middle page programming using the 3-bit LM code. The middle page programming is performed on the basis of the first round, lower page programming. A given middle bit can represent different memory states depending on the lower bit. In the second round of programming, if a cell is to have the middle bit as "1" while the lower bit is at "1", i.e. (x,1,1), there is no programming for that cell and it remains in "Gr". If the middle bit is "0" while the lower bit is at "1", i.e., (x,0,1), the cell is programmed from the "Gr" state to a first "middle intermediate" state straddling between "A" and "B". During programming to the first "middle intermediate" state, the verifying is relative to the demarcation DV_A. On the other hand, if the cell is to have the middle bit as "0" while the lower bit is at "0", i.e., (x,0,0), the cell is programmed from the "lower intermediate" state to a second middle intermediate" state straddling between "C" and "D". The program verifying is relative to a demarcation DV_C. Similarly, if the cell is to have the middle bit as "1" while the lower page is at "0", i.e., (x,1,0), the cell will be programmed from the "lower intermediate" state to a third "middle intermediate" state straddling between "E" and "F". The program verifying is relative to a demarcation DV_E.

FIGS. **25**(**3**) and **25**(**4**) illustrate the upper page programming using the 3-bit LM code. The upper page programming is performed on the basis of the first and second rounds, namely the lower and middle page programming A given upper bit can represent different memory states depending on the lower and middle bits. In the third round of programming, if a cell is to have the upper bit as "1" while the lower and middle bits are at "1", i.e. (1,1,1), there is no programming for that cell and it remains in "Gr". On the other hand, if the upper bit is "0" while the lower and middle bits are at "1", i.e. (0,1,1), the cell is programmed from the "Gr" state to the "A" state. During programming to "A", the verifying is relative to the demarcation DV_A.

Similarly, if the cell is to have the upper bit as "0" while the lower bit and middle bits are at "0" and "1" respectively, i.e. (0,0,1), the cell is programmed from the first "middle intermediate" state to "B". The program verifying is relative to a demarcation DV_B. If the cell is to have the upper bit as "1" while the lower bit and middle bits are at "0" and "1" respectively, i.e. (1,0,1), the cell is programmed from the first "middle intermediate" state to "C". The program verifying is relative to a demarcation DV_C.

Similarly, if the cell is to have the upper bit as "1" while the lower bit and middle bits are at "0" and "0" respectively, i.e. (1,0,0), the cell is programmed from the second "middle intermediate" state to "D". The program verifying is relative to a demarcation DV_D. If the cell is to have the upper bit as "0" while the lower bit and middle bits are at "0" and "0" respectively, i.e. (0,0,0), the cell is programmed from the second "middle intermediate" state to "E". The program verifying is relative to a demarcation DV_E.

Similarly, if the cell is to have the upper bit as "0" while the lower bit and middle bits are at "1" and "0" respectively, i.e. (0,1,0), the cell is programmed from the third "middle intermediate" state to "F". The program verifying is relative to a demarcation DV_E. If the cell is to have the upper bit as "1"

while the lower bit and middle bits are at "0" and "0" respectively, i.e. (1,1,0), the cell is programmed from the third "middle intermediate" state to "G". The program verifying is relative to a demarcation DV_G.

Since the upper page programming only involves programming to the next adjacent memory state from either the "Gr" state or one of the "middle intermediate" states, no large amount of charges is altered from one round to another. This helps to alleviates BL-BL Yupin effect.

Thus, it will be seen that a Dm (m=1, 2, 3, . . .) memory can be programmed a bit at a time and also read a bit at a time. When a group of memory cells on a word line WLn are programmed or read in parallel, there will be m data pages associated with the group, with each data page corresponding to one bit from each cells of the group. In a progressive reading mode, the sensing is relative to a subset of the reference thresholds and at each sensing only one of the m data pages are read from WLn and transferred out to the controller. In a full sequence reading mode, the sensing is relative to all the reference thresholds and all m data pages are read from WLn before being transferred out page by page.

For example, in the case of a memory with the NAND architecture shown in FIG. **4**, each NAND string has a daisy chain of n memory cell. In one embodiment, a row of such NAND chains forms an erase block **300** shown in FIG. **6**. In FIG. **4**, a page of memory cells, such as page **70** on WL**3**, is operated on in parallel.

FIG. **9** shows a data page **70'** being one of the m data pages for an m-bit memory on word line WLn. As described earlier, in another preferred embodiment, when with higher and higher device integration, there are larger than optimal number of memory cells in a page sharing an ECC field, the page **70** is partitioned into smaller units, consisting of "ECC pages".

FIG. **26**A illustrates schematically an ECC page containing an ECC field similar to that shown in FIG. **9**. The ECC page **80** comprises a user portion **82** and a system portion **84**. The user portion **82** is for storage of user data. The system portion **84** is generally used by the memory system for storage of system data. Included in the system data is an ECC. The ECC is computed for the ECC page. Typically, the ECC is computed by the ECC processor **62** in the controller **102** (see FIG. **1**.) The difference between FIG. **26**A and FIG. **9** is that instead of the ECC page **80** of occupying the entire data page **70'**, it is one of several constituting the data page.

FIG. **26**B illustrates a plurality of ECC pages constituting a data page. A data page such as the data page **70'** shown in FIG. **4** is the set of data constituted from a logical bit from each cell of a page of cells on a WL. In general there are N EEC pages making up a data page. For example, N=4, where there are 4 EEC pages **80** making up one data page **70'**.

As data is received from a host, an ECC page of data is staged in the controller **102** and its ECC **86** is computed by the ECC processor **62** (see FIG. **1**). A number of ECC pages **80** incorporating their own ECC is then staged and written to the memory array **200** as a data page **70'**. Typically, when the data page **70'** is read, the data page is latched in the data latches **430** and shifted out of the I/O circuits **440** to the controller **102**. At the controller **102**, each ECC pages of the data page's has its ECC **86** compared to a second version of the ECC computed on the read data. The ECC typically includes an error detection code ("EDC") for rapid detection of any error in the data page. If the EDC indicates the existence of any error in the read data page, the ECC is invoked to correct erroneous bits in the read data page. The ECC is designed to correct up to a predetermined maximum number of errors. In practice, at any given time in the life of a memory, the ECC may have budget to correct a predetermined number of errors less than the predetermined maximum.

For a 2-bit memory, each cell stores 2 bits of data and there will be 2 data pages associated with each WL in the example in FIG. **4**. If each data page has 4 ECC pages, then there will be a total of 8 ECC pages programmed into a WL and to be read out for PWR checking.

Similarly for a 3-bit memory, each cell stores 3 bits of data and there will be 3 data pages associated with each WL in the example in FIG. **4**. If each data page has 4 ECC pages, then there will be a total of 12 ECC pages programmed into a WL and to be read out for PWR (post-write read) checking.

Thus, it will be seen for a 3-bit memory that performing a PWR check after writing every WL can involve sensing the 12 ECC pages and then shipping out to the controller for ECC checking. If the ECC decoder finds any one of the 12 ECC pages has exceeded a predetermined error budget, the write to that WL is deemed unacceptable and is retried at a different WL. For example, the write is rewritten to another WL in the same block or in a portion of memory, such as with one-bit cells, having a higher tolerance for errors.

In the 3-bit memory example, there are 3 data page to be sensed. As seen from the description in connection with FIG. **25**, this will incur 3 read cycles, one for each data page. Each read cycle will be sensing relative to one or more reference thresholds and therefore reading the WL will take time. Furthermore, each data page has 4 ECC pages and a total of 12 ECC pages will need to be serially transferred out to the controller. The transfer operations will also take time, if not more time than the sensing operations.

PWR Checking on a Sample Instead of the Whole Population

In a general embodiment of the invention, the post-write read (PWR) checking on what has been written is accelerated by checking only a subset of what has been written. The post-write read checking is performed on only a sample of what was written.

FIG. **27** is a flow chart illustrating the general embodiment of accelerated PWR.

STEP **900**: Providing multiple groups of memory cells, the memory cells in each group for operating in parallel.

STEP **902**: Programming multiple subsets of data into a first group of memory cells, each subset of data being provided with an ECC.

STEP **910**: Selecting a sample of the data programmed in the first group of memory cells, the sample being selected from a subset of data said multiple subsets of data programmed into the first group.

STEP **920**: Reading said sample.

STEP **922**: Checking said sample for errors.

STEP **930**: Reprogramming said multiple subsets of data into a second group of memory cells whenever the errors checked from the sample is more than a predetermined number of error bits.

In one embodiment, the sample to be check is a subset of all the ECC pages written to a group of cell on a word line. In particular, the subset is one among all the ECC pages that is estimated to have a highest error rate.

FIG. **28** is a flow chart illustrating a preferred embodiment of accelerated PWR illustrated in FIG. **27**. The process is similar to that of FIG. **27**, except STEP **910** is replaced by STEP **910'**.

STEP **910'**: Selecting a sample of the data programmed in the first group of memory cells, the sample being selected from a subset of data said multiple subsets of data programmed into the first group and the sample is a subset of data

estimated to have a highest error rate among said multiple subsets of data programmed into the first group.

FIG. **29** illustrates a sample selected for post-write read after a group of 3-bit memory cells on a word line has been written. In the 3-bit memory, there will be 3 data pages, namely, lower, middle and upper pages, written to a word line WL **42**. Depending on the designed placement of the reference thresholds that demarcate the various voltage bands in the threshold window of the memory, one of the data pages may have a slightly higher error rate than the other. For example, if the upper data page has an estimated highest data rate among the three data pages, it will be selected. If all the ECC pages in the selected data page are estimated to have the same error rate, then it suffices to select an ECC page with a location that is the first to be shifted out to the controller. Also, the choice of coding scheme can also have a bearing on the error rate. For example, a grey code offers a minimum bit error when the programmed threshold is shifted. Depending on the choice of coding, the various data pages being stored in the same group of memory cells can have similar or different error rates.

In practice, the error on a word line could be due to a physical defect like a crack resulting in an open circuit or one with an unusually high resistance. If the defect occurs between the cell in question and the WL decoder, the check will show an error. If the defect occurs on the other side of the cell away from the WL decoder, then, the check may not show an error. Thus, among all the ECC pages along the WL **42**, the sample ECC page **82** at the end of the WL furthest from the WL decoder **40** is likely to be impacted by the defect irrespective of the defect location on the WL.

Thus, in a preferred embodiment where there are multiple data pages written to a word line (WL), a sample used for checking the data written to the WL is first selected from a data page with highest estimated error rate. Furthermore, if there are multiple ECC pages in the selected data page, the ECC page located furthest away from a word line decoder is selected for the sample.

In another embodiment, the sample to be check is a subset of all the ECC pages written to a group of cells in a block. The block has all cells in it erasable together. In particular, the subset is one among all the ECC pages that is estimated to have a highest error rate.

For example, in the NAND memory shown in FIG. **4**, an erase block is constituted from a row of NAND chains. Each NAND chain is 16 memory cells daisy-chained by their sources and drains, terminating on one end in a source terminal and the other end in a drain terminal. It is well-known that the cells in closest to the source terminal and the drain terminal are more error prone. Thus, for such a block, the word lines WL**1** or WL**16** should be selected. In this case, preferably, the sample is the ECC page at the end of WL**1** furthest from the word line decoder.

In yet another embodiment, where a block of memory cell having a set of word lines is erasable as a erase unit, and there is a requirement that data written to each word line of the set must check out, or else the entire block is rewritten, the WL of the set estimated to have the highest error rate is preferentially checked first. In this way, any error that may occur will be detected early and the rewriting of the block can begin without delay.

Thus, for the NAND memory shown in FIG. **4**, the word lines WL**1** and WL**16** should be selected first for checking.

Although an example is given for a memory being partitioned into a first portion having memory cells each storing 1-bit data and a second portion having memory cells each storing 3-bit data, the invention is not limited by the example.

The foregoing detailed description of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed. Many modifications and variations are possible in light of the above teaching. The described embodiments were chosen in order to best explain the principles of the invention and its practical application, to thereby enable others skilled in the art to best utilize the invention in various embodiments and with various modifications as are suited to the particular use contemplated. It is intended that the scope of the invention be defined by the claims appended hereto.

It is claimed:

1. A method of operating a non-volatile memory, comprising:

providing multiple groups of memory cells, the memory cells in each group for operating in parallel;

programming an original copy of multiple subsets of data into a first group of memory cells, each subset of data being provided with an ECC;

performing a post write read of the first group of memory cells by:

selecting a sample of the first group of memory cells corresponding to a subset of data with associated ECC;

checking said sample for errors by processing with the associated ECC, and

reprogramming said original copy of multiple subsets of data into a second group of memory cells whenever the errors checked from the sample is more than a predetermined number of error bits, and wherein the first and second groups of memory cells each forms a block of memory cells that is a minimum erase unit.

2. The method as in claim **1**, wherein:

the sample is a subset of data estimated to have a highest error rate among said multiple subsets of data programmed into the first group.

3. The method as in claim **1**, wherein:

each memory cells of the first group stores n bits of data;

said programming multiple subsets of data stores n data pages into the first group of memory cells, each data page constituted by one bit from each memory cell in the first group.

4. The method as in claim **3**, wherein:

n is equal to 3.

5. The method as in claim **1**, wherein:

said checking for errors include checking the ECC of the sample to determine the number of error bits.

6. The method as in claim **1**, further comprising:

configuring said non-volatile memory into first and second portions, the first portion having memory cells operating with less error rate but lower density storage compared to the second portion; and wherein:

said first and second groups of memory cells are in the first portion; and

said second group of memory cells is in the second portion.

7. The method as in claim **1**, further comprising:

configuring said non-volatile memory into first and second portions, the first portion having memory cells operating with less error rate but lower density storage compared to the second portion; and wherein:

said first group of memory cells is in the first portion; and

said second group of memory cells is in the second portion.

8. The method as in claim **1**, wherein:

the memory is further organized into multiple rows of NAND chains;

each NAND chain being a column of a string of daisy-chained memory cells terminating at a source terminal and a drain terminal; and

the sample is a subset of data stored at memory cells closest to the source terminal of each NAND chain.

9. The method as in claim **1**, wherein:

the memory is further organized into multiple rows of NAND chains;

each NAND chain being a column of a string of daisy-chained memory cells terminating at a source terminal and a drain terminal; and

the sample is a subset of data stored at memory cells closest to the drain terminal of each NAND chain.

10. A non-volatile memory, comprising:

multiple groups of memory cells, the memory cells in each group for operating in parallel;

a programming circuit for programming an original copy of multiple subsets of data into a first group of memory cells, each subset of data being provided with an ECC;

a sample of the data programmed in the first group of memory cells, the sample being a subset of data among said multiple subsets of data programmed into the first group;

a reading circuit for reading said sample including an associated ECC;

an ECC decoder for performing a post write read to check said programming by checking errors in said sample by processing with the associated ECC, and

a reprogramming circuit for reprogramming said original copy of multiple subsets of data into a second group of memory cells whenever the errors checked from the sample is more than a predetermined number of error bits, and wherein the first and second groups of memory cells each forms a block of memory cells that is a minimum erase unit.

11. The non-volatile memory as in claim **10**, wherein:

the sample is a subset of data estimated to have a highest error rate among said multiple subsets of data programmed into the first group.

12. The non-volatile memory as in claim **10**, wherein:

each memory cells of the first group stores n bits of data;

said programming multiple subsets of data stores n data pages into the first group of memory cells, each data page constituted by one bit from each memory cell in the first group.

13. The non-volatile memory as in claim **12** wherein:

n is equal to 3.

14. The non-volatile memory as in claim **10**, wherein:

said ECC decoder checks the ECC of the sample to determine the number of error bits.

15. The non-volatile memory as in claim **10**, further comprising:

first and second portions, the first portion having memory cells operating with less error rate but lower density storage compared to the second portion; and wherein:

said first and second groups of memory cells are in the first portion; and

said second group of memory cells is in the second portion.

16. The non-volatile memory as in claim **10**, further comprising:

first and second portions, the first portion having memory cells operating with less error rate but lower density storage compared to the second portion; and wherein:

said first group of memory cells is in the first portion; and

said second group of memory cells is in the second portion.

17. The non-volatile memory as in claim **10**, wherein:

the memory is further organized into multiple rows of NAND chains;

each NAND chain being a column of a string of daisy-chained memory cells terminating at a source terminal and a drain terminal; and

the sample is a subset of data stored at memory cells closest to the source terminal of each NAND chain.

18. The non-volatile memory as in claim **10**, wherein:

the memory is further organized into multiple rows of NAND chains;

each NAND chain being a column of a string of daisy-chained memory cells terminating at a source terminal and a drain terminal; and

the sample is a subset of data stored at memory cells closest to the drain terminal of each NAND chain.

* * * * *