



ECC and Signal Processing
Technology for Solid State Drives
and Multi-bit per cell NAND Flash
Memories
2nd edition

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Contents

CONTENTS	III
LIST OF FIGURES	VII
LIST OF TABLES	XI
EXECUTIVE SUMMARY	12
INTRODUCTION	13
HARD DISK DRIVE TRENDS.....	14
The Read Channel.....	16
Peak-to-Peak Detection	18
Partial Response Maximum Likelihood (PRML)	20
Error Correction	30
Outlook	32
NAND FLASH MEMORY OVERVIEW	35
NAND Flash Memory Introduction.....	35
Concept.....	35
NAND Flash Architecture	37
Scalability	39
NAND FLASH MEMORY RELIABILITY.....	43
Random Telegraph Noise	43
Program Noise.....	45
Dopant Fluctuation, Line Edge Roughness	47
Bit Errors.....	49
Program Disturb	50
Read Disturb	51
Charge Leakage	53
SHANNON LIMIT	56
ERROR CORRECTION CODES.....	59
Types of Codes	59
Block Codes.....	59
Convolutional Codes	59
Concatenated Codes	60
Hamming Code.....	60
BCH Code.....	67
Encoding.....	68
Decoding.....	68

Reed-Solomon Code	73
Encoding.....	75
Decoding.....	76
BCH and Reed-Solomon Considerations	77
Convolutional Codes	80
Encoding.....	80
Decoding.....	82
Performance.....	83
Trellis Coded Modulation.....	85
Concatenated TCM-BCH Coding.....	87
Turbo Codes	89
Encoding.....	90
Decoding.....	91
Performance.....	92
Low Density Parity Check (LDPC)	93
Representations for LDPC codes	94
Regular and Irregular LDPC codes.....	95
Constructing LDPC codes	95
Performance & Complexity	96
Decoding LDPC codes.....	96
Hard-decision Decoding.....	96
Soft-decision Decoding.....	98
Encoding.....	101
LDPC in NAND Flash Memories.....	101
Summary	101
Outlook	102
SIGNAL PROCESSING FOR FLASH MEMORIES.....	103
ECC for Flash Memories	103
Adaptive/Dynamic ECC Scheme	104
BCH and Shannon Limit	107
SLC Soft Detection	108
Test Mode Sequences	110

Soft Read	110
MLC Soft Detection	111
Sensing Schemes.....	112
Analog Sensing.....	113
Moving Reference	116
MLC Programming with ECC.....	121
Floating Gate Coupling Compensation	124
Fractional Reference Voltage Threshold	127
State Ordering	128
Statistics Collection	130
Inter-cell Interference Cancellation.....	130
Adaptive Program and Read.....	131
Data Scrambling.....	131
Asymmetric Coding	132
NAND Capacity Gains.....	134
Endurance Improvement.....	135
Controller Level Techniques.....	137
Summary	137
COMPETITIVE LANDSCAPE.....	138
Roadmap	138
Competencies of Flash Signal Processing Players	139
Players	141
xxxxxxx.....	141
xxxxxxx.....	142
xxxxxxx.....	143
xxxxxxx.....	144
xxxxxxx.....	145
xxxxxxx.....	150
xxxxxxx.....	150
xxxxxxx.....	150
xxxxxxx.....	151
xxxxxxx.....	151

XXXXXXXX	152
XXXXXXXX	154
XXXXXXXX	157
XXXXXXXX	158
XXXXXXXX	159
XXXXXXXX	159
XXXXXXXX	160
XXXXXXXX	160
XXXXXXXX	160
XXXXXXXX	163
XXXXXXXX	163
XXXXXXXX	164
XXXXXXXX	164
Outlook	164
MARKET FOR FLASH SIGNAL PROCESSING TECHNOLOGY	166
Cost	166
Consumer low end NAND applications (Removable storage)	171
Embedded Consumer NAND applications	171
Consumer SSD NAND applications	172
Enterprise SSD NAND applications	172
Applications	172
SUMMARY	176
REFERENCES	CLXXVII
TERMINOLOGY	CLXXXII
ABOUT THE AUTHORS	CLXXXIV
ABOUT FORWARD INSIGHTS	CLXXXVI
Services	clxxxvi
Contact	clxxxvi
REPORT OFFERINGS	CLXXXVIII

List of Figures

Figure 1. HDD Areal Density Trend..... 14

Figure 2. HDD Performance Trend..... 15

Figure 3. Storage Pricing Trends 16

Figure 4. HDD Communications Model..... 17

Figure 5. Readback Signal 17

Figure 6. Peak Detection..... 18

Figure 7. Effect of Increased Recording Density..... 19

Figure 8. PRML Read Channel Architecture..... 21

Figure 9. Superposition of Pulses 22

Figure 10. Maximum Likelihood Detection 24

Figure 11. Partial Response Schemes 26

Figure 12. Eye Diagrams for PR4 and EPR4 Channels..... 28

Figure 13. Eye Diagram for EPR4 (1,7) Channel 28

Figure 14. Waveform and Interleaved Sequences for RLL (0,4/4)..... 29

Figure 15. Diminishing Returns on 512B Sector ECC 30

Figure 16. ECC Gains with Increased Sector Size..... 31

Figure 17. Signal Processing and Coding Trends 32

Figure 18. LDPC vs. PR4, EPR4 and NPML 33

Figure 19. Iterative Decoding 34

Figure 20. NAND Flash Cell Programming 35

Figure 21. Multi-level Storage in NAND Flash..... 35

Figure 22. NAND Flash Cell Reading 36

Figure 23. NAND Flash Cell Erase 36

Figure 24. NAND Cell Architecture 37

Figure 25. NAND Cell String 37

Figure 26. NAND Flash Memory Architecture 38

Figure 27. 8Gb NAND Flash Memory Organization..... 38

Figure 28. Cross-talk and Coupling Ratio 39

Figure 29. Inter-cell Interference 40

Figure 30. Multi-bit per Cell NAND Flash Endurance..... 40

Figure 31. Electrons Stored on the Floating Gate 41

Figure 32. NAND Flash Bit Size Trend..... 42

Figure 33. V_t Fluctuation due to RTN 43

Figure 34. Number and Amplitude of Trap Sites..... 44

Figure 35. Dependence of Traps on P/E Cycles 44

Figure 36. S/N in Multi-level NAND Flash Memories..... 45

Figure 37. ISPP and ΔV_t Spread 46

Figure 38. Effect of Program Injection 47

Figure 39. σV_t vs. Channel Length due to Random Discrete Dopants in the Source and Drain of Double Gate MOSFETs 47

Figure 40. Effect of Gate Oxide Thickness on V_t 48

Figure 41. Line Edge Roughness 48

Figure 42. Uncorrectable BER vs. Raw BER 49

Figure 43. Flash Error Rate Surface..... 50

Figure 44. Program Disturb 50

Figure 45. RBER vs. P/E Cycling..... 51

Figure 46.	Read Disturb	52
Figure 47.	RBBER vs. Number of Reads	52
Figure 48.	Effect of Number of Electrons per Bit on Retention Time	53
Figure 49.	RBBER vs. Retention	54
Figure 50.	MLC NAND Flash Endurance & Data Retention	55
Figure 51.	Soft Decoded Multi-bit/cell Limits and Hard Decoded 1bit/cell Limit vs, Shannon Limit	57
Figure 52.	Code Gain and Distance Limit	58
Figure 53.	Representation of the Hamming Coding and Decoding	60
Figure 54.	Encoding and Decoding for Systematic Hamming	62
Figure 55.	Representation of the matrix M systematically built on the basis of the data flow (m_i) going through the memory. The sorting indexes x (1-512) and y (1-8) univocally identify each bit of the matrix M and are therefore suitable for building the parity matrix H	63
Figure 56.	Representation of the matrix H . The sorting indexes x (1-512) and y (1-8), univocally identify each row of the matrix H (a). For the calculation of the parity and of the syndrome, the matrix H is seen as the composition $((Y,X)^T, I)$. The matrix H is completed by adding the necessary row and column for the code extension.	64
Figure 57.	Representation of the matrix M systematically built on the basis of the data flow going through the memory. The sorting indexes x (0-511) and y (0-7) univocally identify each bit of the matrix M and are therefore suitable for building the parity matrix	65
Figure 58.	Representation of the matrix H . The sorting indexes x (0-511) and y (0-7), univocally identify each row of the matrix H (a). For the parity and the syndrome calculation, the matrix H is seen as the composition $((Y, Y', X, X')^T, I)$ (b)	66
Figure 59.	BER/EDR for Hamming ECC	67
Figure 60.	BCH Encoding and Decoding	68
Figure 61.	BERout vs. E_b/N_0 for a 2KB Page SLC NAND Flash Device for Hamming and BCH Code	72
Figure 62.	Channel Capacity - Hamming Code and BCH Code for 1, 2, 3, 4 bits/cell.	73
Figure 63.	Structure of a Reed-Solomon Code	75
Figure 64.	R (Ratio) vs. t (Number of Error Corrected) for BCH	78
Figure 65.	Channel Capacity - BCH vs. Reed-Solomon	79
Figure 66.	BERout vs. E_b/N_0 for a 2KB Page SLC Device for Reed-Solomon Code	79
Figure 67.	Convolutional Encoder	80
Figure 68.	Constraint Length 3 Convolutional Encoder State Diagram	81
Figure 69.	Constraint Length 3 Convolutional Encoder Trellis Diagram	81
Figure 70.	Constraint Length 3 Convolutional Encoder Trellis Diagram for Input Sequence (1 0 0 1 1 0 1 0)	82
Figure 71.	Convolutional Code Performance (Upper Limit)	84
Figure 72.	Convolutional code $R = 1/2$, $k = 3, 8, 14$ on Channel Capacity Plane.	85
Figure 73.	TCM Error Correction System	85
Figure 74.	BER Performance TCM, BCH & Hamming Code for 16-bit, 32-bit and 64-bit User Data	86
Figure 75.	Program (a) and Read (b) in TCM Error Correction System	87
Figure 76.	t for BCH Code	87
Figure 77.	BER handled by BCH Code as a Function of Deviation of V_t Width Distribution σ	88
Figure 78.	Cell Storage Efficiency	89
Figure 79.	Basic Turbo Encoder	90
Figure 80.	Basic Turbo Code Decoder	91

Figure 81. Performance of Turbo Code. BER given by Iterative Decoding ($p = 1, \dots, 18$) at a rate $R = 1/2$ Encoder, Memory $v = 4$, generators $G1 = 37$, $G2 = 21$, with interleaving 256×256 .	92
Figure 82. LDPC Performance as a Function of Block Length	94
Figure 83. Tanner Graph of Parity Check Matrix	95
Figure 84. Overview over messages received and sent by the c-nodes in step 2 of the message passing algorithm	97
Figure 85. Step 3 of the described decoding algorithm. The v-nodes use the answer messages from the c-nodes to perform a majority vote on the bit value.	98
Figure 86. a) Illustrates the calculation of $r_{ji}(b)$ and b) $q_{ij}(b)$	99
Figure 87. Approaching the Shannon Limit	102
Figure 88. Page Size + Spare Area Trend	104
Figure 89. Codewords of Four Operation Modes for Adaptive BCH ECC	105
Figure 90. Dynamic ECC Codeword Transition Scheme	106
Figure 91. Dynamic ECC codeword transition by (a) monitoring the number of errors (b) monitoring the number of W/E cycles	106
Figure 92. Shannon Limit and BCH ECC for Multi-level NAND Flash Memories	107
Figure 93. SLC Soft Detection	108
Figure 94. SLC Soft Decoding (5 – 3 Level) with LDPC vs. Hard Decision + BCH 32-bit correction	109
Figure 95. SLC vs. MLC Soft Decoding Limits	112
Figure 96. DSM Sensing	113
Figure 97. Linear Dependency Between N and I_{cell} in the DSM Page Buffer Architecture	114
Figure 98. 4-Level Distribution with References R1, R2 and R3	116
Figure 99. Widened 4-Level Distribution with References	116
Figure 100. Shifted 4-Level Distribution with References	117
Figure 101. Effect of Read Disturb on 4-Level Distribution	117
Figure 102. Effect of Temperature on V_t Distribution	118
Figure 103. Moving Reference Algorithm	119
Figure 104. Moving Reference ECC	119
Figure 105. Program Page Sequence to Minimize FG Coupling	121
Figure 106. WL0 after Programming of Page 0	121
Figure 107. WL0 after Programming of Page 1	122
Figure 108. Marginal cell can be moved to the wrong distribution (red arrow) if an error occurs in the initial read inside the program flow	122
Figure 109. 8-level and 16-level Programming	123
Figure 110. Programming Sequence for 4bit/cell NAND flash and ECC Activity	124
Figure 111. Observed Cell and Neighbouring Cells	125
Figure 112. Observed Cell Programmed at 1V and Neighboring Cells Programmed at -2V	125
Figure 113. V_t Shift due to FG Coupling	127
Figure 114. Fractional Reference V_t for 8-level Cell Memory	128
Figure 115. Serially Ordered 16-level Cell Memory	129
Figure 116. 16-level Cell Memory Ordering for Optimizing Bit Errors	129
Figure 117. Pattern Dependency of Data Retention and Program Disturb Errors	132
Figure 118. Proportion of the data retention error to the program disturb error	133
Figure 119. Asymmetric Coding	133
Figure 120. Improvement in Data Retention Error due to Asymmetric Coding	134
Figure 121. Probability Processing vs. Digital Processing	141
Figure 122. LEC Footprint	142
Figure 123. Performance of LDPC on 3 Bits / Cell Flash Memory	144

Figure 124. xxxxxxxx ECC under Hard Decoding.....	147
Figure 125. xxxxxxxx ECC under Soft Decoding	147
Figure 126. xxxxxxxx Hard and Soft Decoding vs. Hamming.....	148
Figure 127. xxxxxxxx Soft Decoding vs. BCH 24-bit/1kB.....	148
Figure 128. Reverse Concatentation Read Channel Coding.....	150
Figure 129. Marvell Flash Read Channel based on Conventional HDD Read Channel.....	153
Figure 130. Marvell Flash Read Channel	153
Figure 131. Block Diagram of Controller and Flash Memory.....	155
Figure 132. Effect of Storage Genetics Processing Engine	156
Figure 133. Storage Genetics Correction Engine - 4 bit/cell NAND.....	156
Figure 134. ClearNAND.....	157
Figure 135. HB and SB Decoding Process	158
Figure 136. OLEA-BCH vs. Normal BCH Architecture, 8kB page size; 8KB, BSC channel, random error model; 8 BCH blocks per page; Code Rate: 0.9609, 24bits/1024B.....	161
Figure 137. PAC LDPC vs. Normal LDPC Architecture, AWGN channel; Code Rate: 0.9362; 3- bit soft information; min-sum algorithm; 8 iterations.....	161
Figure 138. Weight Control Code, 4kB Page Size; 15/16bit / 512Byte BCH; Raw ER : 1.8×10^{-3}	162
Figure 139. Maximum Frequency and Power Consumption vs. Supply Voltage.....	167
Figure 140. a) Normalized Voltage Supply vs. Parallelism, b) BER vs. Maximum Number of Iterations under 4-bit quantized minsum decoding - Reed-Solomon based (6, 32)-regular 2048-bit LDPC code.....	167
Figure 141. LDPC Decoder Die Photo	168
Figure 142. A Parallel RS-LDPC (2048,1723) for 10GBASE-T Ethernet	170
Figure 143. Applications Utilizing NAND Flash	173
Figure 144. Flash Signal Processing Cost Adder.....	173
Figure 145. NAND Flash Solution by Implementation	174
Figure 146. TAM for Advanced ECC/FSP Chips.....	175

List of Tables

Table 1.	Capacities of (0,G/I).....	29
Table 2.	Comparison of Detection Methods	30
Table 3.	TCM vs. Hamming & BCH	86
Table 4.	Silicon Area (mm ²)	88
Table 5.	ECC Requirements for Multi-level NAND Flash Memories.....	103
Table 6.	Adaptive ECC Scheme Performance	105
Table 7.	Capacity Increase – LDPC vs. BCH	135
Table 8.	Endurance Increase – LDPC vs. BCH	136
Table 9.	Controller-level Techniques.....	137
Table 10.	Planned Deployment of DSP Techniques by NAND Flash Vendor.....	138
Table 11.	Planned Product Deployment of NAND Flash Vendors Employing DSP Techniques	139
Table 12.	Competencies of Flash Signal Processing Players.....	140
Table 13.	Coding Gain.....	145
Table 14.	xxxxxxx ECC Hardware Implementation.....	146
Table 15.	Comparison of DBECC, LDPC and BCH	149
Table 16.	Endurance Specifications with ECC Engine.....	154
Table 17.	EZ-NAND Architecture vs. Traditional Architecture.....	158
Table 18.	LDPC Error Correction Capability	159
Table 19.	xxxxxxx SSD Controllers	163
Table 20.	Comparison of LDPC Decoders	169
Table 21.	Core Area for 2.5 million Gates.....	169

Introduction

In December 2011, it was widely reported that Apple had acquired Anobit Technologies for half a billion dollars. *What prompted Apple to spend that kind of money on a five year old startup?* As the biggest consumer of NAND flash memories, this was clearly a strategic acquisition. The tie-up follows a less widely known acquisition of Storage Genetics by Micron Technology in 2010. Both Anobit and Storage Genetics were developing advanced ECC and signal processing technologies.

As bit errors increase as NAND flash memory scales below 2xnm process technology and transitions to 3-bit per cell architectures, traditional error correction codes such as BCH, RS and Hamming code will no longer be sufficient. These codes suffer from increased overhead in terms of coding redundancy and read latency as the number of errors corrected increases. In addition, the number of electrons stored in the memory cell is decreasing with each generation of flash memory resulting in reduced signal/noise requiring enhanced sensing techniques.

Digital signal processing technology has been employed in the magnetic recording industry since the early 1990's when partial-response maximum-likelihood technology (PRML) was commercialized. DSP technology is now being deployed in 3-bit per cell NAND flash memories and a concerted effort is being made by NAND flash manufacturers and a handful of startups to employ digital signal processing technology to improve the endurance and performance of next generation NAND flash memories and solid state drives. Signal processing technology will be essential for the continued scaling of NAND flash memories.

This research report examines the current state of ECC techniques and explores the technology, roadmap, market, cost and competitive landscape in the flash signal processing space.

About the Authors

Vikas Agrawal was Senior Market Analyst for storage system (SSD/HDD) controllers and markets. His expertise lies in understanding the technology, competitive landscape and market trends for storage components, on-chip and off-chip memory, **storage networking** and **storage system markets**.

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Vikas received his MBA from Southern Methodist University, Dallas in 2002 and Masters in Electrical Engineering from Arizona State University in 1995. He holds six memory-related patents for networking, digital signal processors and wireless products.

Roberto Ravasio was Senior Technical Analyst for DSP, Flash Algorithms and ECC. Roberto has 15 years of experience in **MLC NAND** and **NOR flash design, algorithms** and **hardware for digital signal processing, wireless base band channels** and **error correction codes**. Previously, Roberto was team leader for the design of the 16Gb 36nm floating gate NAND flash memory at Qimonda AG where he was responsible for the architecture definition of the device including matrix organization and device floor plan, HV circuits hierarchical control, ECC and redundancy, embedded controller and compiler, embedded RAM, ROM and Fuse-ROM, DFT custom structure, ONFI Command Interface, high-speed data path, logic design and integration (Front End) and VHDL full chip modeling for recursive test. He also contributed to the development of the MLC algorithm for 48nm NAND flash memory.

Roberto was also team leader of 60nm and 90nm MLC NAND flash products and 0.13 μ m and 0.18 μ m NOR flash products at STMicroelectronics.

He is the author/co-author of 25 U.S. patents and the following books: **Error Correction Codes for Non-Volatile Memories**, **Memories in Wireless Systems** and **VLSI-Design of Non-Volatile Memories**.

Roberto received his Masters degree in Electronic Engineering at the Polytechnic of Milan in 1996.

Gregory Wong is Founder and Principal Analyst. Greg has in-depth knowledge of the cost, performance and markets and applications of **2-bit per cell NOR, NROM and NAND flash, 3-bit per cell and 4-bit per cell NAND and 4-bit per cell NROM flash technologies** as well as **solid state drives**. He also tracks wafer capacity and NAND and SSD shipments.

Greg has 11 years of management experience in strategic planning, business development, competitive intelligence and engineering at Hitachi, Siemens, ProMOS and Qimonda/Infineon. In these positions, Greg was responsible for analyzing and evaluating flash memory vendors' strategies, process technologies, design architectures, product performance, manufacturing capabilities and costs. Greg worked closely with senior management on strategy formulation and setting operational performance targets. He has worked in Canada, Japan, China, Taiwan and Germany.

Greg earned his B.A.Sc. degree in Electrical Engineering from the University of Toronto, and his M.B.A. degree from the Richard Ivey School of Business in London, Ontario.

About Forward Insights

Forward Insights provides independent, insightful market research, consulting and information services focusing on semiconductor memories and solid state storage. The company offers unparalleled depth and understanding of the strategic, market and technical complexities of the semiconductor memory landscape.

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SSD Quarterly Insights

SSD Quarterly Insights is a SSD market forecast published four times a year which includes shipment and capacity data for enterprise and client computing applications.

Low Density SLC NAND Flash Memory in Embedded Applications

In last decade, the NAND flash market has witnessed tremendous growth with revenues increasing from \$370 million in 2000 to over \$20 billion in 2010.

Continuous price declines for NAND flash memory have enabled it diversify beyond removable storage applications to consumer, industrial and computing applications, each with its own specific requirements in terms of performance, features and density.

Since 2006, MLC technology has become mainstream with SLC technology occupying a sliver of the total market. SLC technology is favored in applications requiring high performance, high reliability and wide operating temperatures. Other than the solid state computing and mobile application markets, SLC devices can be found in embedded applications. In particular, low density SLC NAND devices ranging from 128Mb to 4Gb are employed in a variety of consumer and industrial applications.

Due to the higher margin profile of SLC NAND products, NAND flash manufacturers as well as new entrants looking to extend their product portfolios from the NOR flash memory space are all eyeing the low density SLC market.

Low Density SLC NAND Flash Memory in Embedded Applications examines the competition between low density SLC NAND flash, parallel NOR flash and serial flash and sheds light on some of the application drivers for SLC NAND flash memory in the embedded space.

NAND Flash Memory Architecture and Periphery Trends

Analyzes the NAND flash architectural choices affecting the competitiveness of the die area including no. of planes, page buffer layout, interleaved and All Bitline sensing, page size, cell string size, SLC/MLC/8LC/16LC, cell size, wordline fanout, bitlines, ECC and periphery transistors. An examination of the periphery of 3D NAND and cross point memory is also provided.

What's After NAND?

In the near future, floating gate NAND flash is likely to encounter fundamental scaling limitations. A variety of technologies including Toshiba's BiCs, Samsung's VG-NAND, Macronix's BE-SONOS, SanDisk's 3D Memory (RRAM) and Intel/Micron's PCMs (stackable PCM) offer the promise of continued increases in storage capacities and lower cost per bit necessary to enable new and emerging data storage applications.

What's After NAND? provides an in-depth analysis of the post-floating gate NAND flash options and an independent assessment of the viability of these technologies going forward...

Applications for 3-bit per cell/4-bit per cell NAND Flash Memories

This report provides an in-depth analysis of the technology, performance, cost, market and applications for 3-bit per cell and 4-bit per cell NAND flash memories.

Solid State Drive Technology and Applications: A Primer

Solid State Drive Technology and Applications: A Primer is an ideal guide for novices interested in acquiring a basic understanding of SSD technology and applications as well as a handy reference for more experienced professionals. The report provides a detailed overview of the technology, architecture and reliability of SSDs as well as techniques for improving the performance and endurance. The advantages and disadvantages of SSDs versus HDDs in PCs and enterprise computing are examined along with an analysis of enterprise applications appropriate for SSD technology. The report also provides an overview of the competitive landscape for SSDs and relevant industry standards.

SSD Innovations

The unprecedented cost reductions of NAND flash memories in the last few years have driven 35mm film and 1.4" floppy disk to extinction. These first generation storage systems such as SD cards and USB flash drives are primarily removable, low capacity, low cost storage for consumer media.

The next frontier for NAND flash memory is as a hard disk drive replacement or an additional tier in the storage hierarchy. The traditional focus on performance in computing and storage farms now encompasses power savings and green technologies. The main reason is not only due to

environmental concerns but also to reduce the Total Cost of Ownership that is heavily impacted by electricity and cooling costs.

The priorities for solid state storage in the computing environment are dramatically different from those for consumer applications resulting in a new approach in the design of the system architecture. These varying requirements are driven by the different workload and environmental conditions. To satisfy these conditions, the type of memory used – SLC versus MLC – and system level management of wear leveling, garbage collection, FTL, ECC and security are key design considerations.

SSD Innovations focuses on innovative solutions from major industry players such as FusionIO, Intel, Pliant, Sandforce, SanDisk and STEC for improving the performance, endurance and reliability of SSDs. An exploration of the evolution of application requirements in computing applications, performance limitations of flash-based storage systems, trends and industry innovations is provided.

In addition, innovative SSD architectures incorporating new memory technologies, external power supply and linked chain architectures are investigated as future SSD development directions.

Phase Change Memory: Mainstream Ambitions

Phase Change Memory: Mainstream Ambitions outlines the challenges PCM faces as it vies to compete with mainstream charge-based memories. The report examines the feasibility of PCM as a replacement for mainstream semiconductor memories including NOR flash, DRAM and NAND flash and explores the potential of PCM as a storage class memory. An update on the PCM activities of major vendors as well as a market and price forecast based on a detailed roadmap is also provided.

Graphics DRAM

The market for graphics DRAM is currently in a stage of massive changes.

In 2008, the market was well structured with only three of the main DRAM suppliers engaged in this market segment, namely Samsung, Hynix and Qimonda with a combined market share of greater than 90%. However, Qimonda's insolvency in January 2009 has disrupted this oligopoly. In May, Micron announced its intention to enter the Graphics DRAM market, followed by Elpida in August. Both companies managed to acquire know-how from the leftover Qimonda assets. Nevertheless, it will be a challenge for both newcomers to establish themselves in the graphics DRAM market.

This report analyzes the current status of the graphics DRAM market and provides an outlook for the following years.

In the first section, the market for GPUs and related graphics card platforms which is dominated by AMD and nVidia is discussed. An overview of the characteristics of different application segments as well as the current platforms of the two market leaders is provided.

The major part of this report analyses the market for graphics DRAM till 2012. This will include a detailed assessment of the memory I/Os and densities needed with forecasts for bit growth rates and memory speed requirements. An ASP and revenue forecast will be presented as well.

The last section focuses on the competitive situation in the graphics DRAM market. A thorough analysis of the competitive landscape and the competitiveness of the four players is provided. This discussion will be based on the market picture gained in the first two sections and the expected product portfolio and technology roadmaps of the various suppliers.

Key NAND Flash Memory Design Intellectual Property

Technical innovations, particularly in NAND flash memory design are key enablers of multi-level cell NAND flash memories, especially 3-bit per cell and 4-bit per cell technologies. This report identifies important intellectual property related to sensing architectures, source voltage noise compensation, programming algorithms, disturbs reduction, temperature compensation, high voltage switch, coding schemes and error correction codes from Hynix, Micron, Samsung, SanDisk, STMicroelectronics and Toshiba.

Comparison of 3-bit per cell NAND Flash Memories

This report compares the 3-bit per cell NAND flash memory architectures of SanDisk/Toshiba, Hynix and Samsung and analyzes the advantages and disadvantages of each implementation.

Read Architectures for 3-bit and 4-bit per cell NAND Flash Memories

This report explores the theory, basic circuit elements, timings, and key design features of the conventional interleaved architecture versus the all bitline sensing architecture.

Emerging Memories Technologies

Sometime in the next decade, both DRAM and flash memories are expected to face fundamental scaling limitations.

In DRAM, new device structures will be required to overcome short channel effects and junction leakage in the array transistor. In order to maintain the capacitor capacitance of 25fF, high aspect ratio structures and new high-k materials will be required as DRAM scales to 30nm.

NOR flash memory faces challenges in channel length scaling and maintaining the drain bias voltage margin necessary to minimize program disturb.

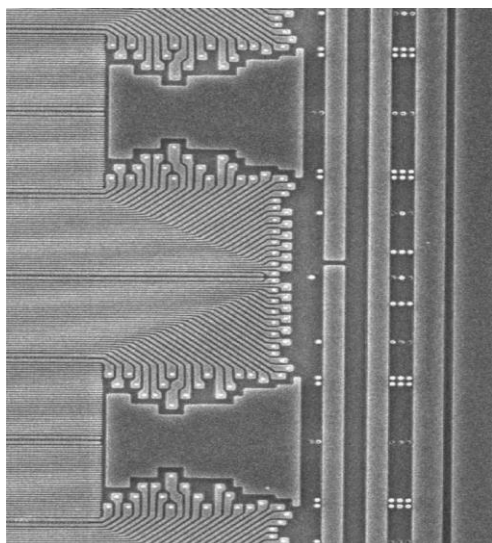
Electrostatic interference between adjacent cells in NAND flash is becoming a serious issue. As geometries shrink, it becomes much more difficult for the ONO dielectric to wrap around the floating gate to maintain the coupling ratio between the control gate and floating gate. Low-k materials

between the cells and high-k materials in the cell will be required for future generations of NAND flash.

As a consequence, DRAM and flash memory vendors are actively researching alternative memory technologies to ensure the continuation of Moore's Law. Technologies such as floating body cell memory and spin-torque MRAM offer the promise of non-volatile RAM-like performance.

Various technologies including phase change memory, charge trap memory, nanocrystal memory, PMC, RRAM and 3D memory are potential candidates to replace flash memory.

Emerging Memory Technologies provides an overview of the challenges facing emerging memory technologies as well as an analysis of the most likely memories to be commercialized in the next five years.



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