



Solid State Drives: A Closer Look

Report No. FI-NFL-SSD-1008

By: Gregory Wong

October 2008

© 2008 Forward Insights. All Rights Reserved. Reproduction and distribution of this publication in any form in whole or in part without prior written permission is prohibited. The information contained herein has been obtained from sources believed to be reliable. Forward Insights does not guarantee the accuracy, validity, completeness or adequacy of such information. Forward Insights will not be liable for any damages or injuries arising from the use of such information including, without limitation, errors, omissions or inadequacies in the information contained herein or for the interpretation thereof. The opinions expressed herein are subject to change without notice.

Contents

CONTENTS	III
LIST OF FIGURES	VI
LIST OF TABLES	IX
EXECUTIVE SUMMARY	1
INTRODUCTION	3
NAND FLASH MEMORY OVERVIEW	4
NAND Flash	4
Concept.....	4
Technology Evolution	6
NAND Flash Architecture	9
NAND Flash Density Trend	11
Page Size Trend.....	13
Block Size Trend.....	14
Read Time.....	14
Program Time	16
Endurance	17
Retention	17
SOLID STATE DRIVES	20
What is a solid state drive?	20
The Memory Hierarchy.....	20
SSD Overview	23
SSD Architecture	26
Controller	28
Flash Translation Layer.....	29
Mapping Schemes	31
Bad Block Management	34
Wear-leveling.....	34
Garbage Collection.....	36
Error Correction	37
Interleaving.....	38
Power Loss Protection	38
Techniques for Improving SSD Performance/Endurance	39
Caching.....	39
Flash File System Optimization	39
Parallelism.....	40

Flash Bus Width	41
Over-provisioning.....	41
Improved NAND Flash Memory	42
Re-mapping of Drive Block	44
Alternative SSD Architectures	46
Chameleon	46
Hybrid SSD.....	47
HyperLink NAND.....	50
SSD Reliability	53
Mean Time Between Failure (MTBF).....	53
Endurance	53
Program Disturb	56
Read Disturb.....	56
Data Retention	57
Bit Error Rate.....	58
SMART	60
SSD vs. HDD	61
Enterprise Applications.....	61
PC Applications	65
Low Cost Mobile PC Applications	69
Price / GB	72
SSD LANDSCAPE	73
Chronology.....	73
Vendor Landscape	74
Standards	75
IDEA	76
JEDEC.....	76
Non-Volatile Memory Host Controller Interface Specification (NVMHCI).....	76
SNIA SSD Initiative	76
SSD Alliance	76
Technical Committee T13 AT Attachment.....	77
Patent Overview	78
Seagate vs. STEC	80
COMPUTING MARKET AND APPLICATIONS	82
Enterprise Market	82

Transaction Processing.....	83
Video Server	83
High Performance Computing.....	85
Internet/Network Server.....	85
Application Workload Characteristics	85
Server-attached vs. Storage-attached SSDs	87
Enterprise SSD Forecast.....	87
Low Cost Mobile PC Market	98
Notebook PC Market.....	105
Desktop PC Market.....	112
Computing SSD Market	116
REFERENCES	CXVIII
ABOUT THE AUTHOR.....	CXX
ABOUT FORWARD INSIGHTS	CXXI
Services	cxxi
Contact	cxxi

List of Figures

Figure 1.	NAND Flash Cell Programming	4
Figure 2.	Multi-level Storage in NAND Flash	4
Figure 3.	NAND Flash Cell Reading.....	5
Figure 4.	NAND Flash Cell Erase	5
Figure 5.	NAND Cell String.....	6
Figure 6.	NAND Cell String.....	6
Figure 7.	NAND Flash Technology Evolution	7
Figure 8.	NAND Flash Memory Gap Fill.....	8
Figure 9.	Electrons Stored on the Floating Gate.....	8
Figure 10.	Samsung 32Gb CTF Memory	9
Figure 11.	NAND Flash Memory Architecture	10
Figure 12.	8Gb NAND Flash Memory Organization.....	11
Figure 13.	NAND Flash Memory Density Trend.....	12
Figure 14.	NAND Flash Memory Chip Size Trend.....	13
Figure 15.	NAND Flash Page Size Trend	13
Figure 16.	NAND Flash Block Size Trend.....	14
Figure 17.	NAND Flash Random Access Time	15
Figure 18.	NAND Flash Read Performance Trend	15
Figure 19.	NAND Flash Program Time	16
Figure 20.	NAND Flash Write Performance Trend	16
Figure 21.	NAND Flash Endurance Trend.....	17
Figure 22.	NAND Flash Endurance Trend at 70nm Technology	19
Figure 23.	NAND Flash Endurance Trend at 3xnm Technology	19
Figure 24.	Memory Hierarchy.....	21
Figure 25.	NAND Flash vs. DRAM Process Technology	22
Figure 26.	Major Components of SSD and HDD	23
Figure 27.	128GB MLC SSD vs. 128GB SLC SSD Bill of Materials	24
Figure 28.	NAND Flash as a % of Bill of Material.....	25
Figure 29.	SSD Architecture	26
Figure 30.	Two-channel, Four-way Interleaving.....	27
Figure 31.	Software Architecture	27
Figure 32.	SSD Controller Functional Block Diagram.....	28
Figure 33.	HDD vs. SSD Address Mapping.....	30
Figure 34.	Flash Translation Layer	30
Figure 35.	Page Mapping	32
Figure 36.	Block Mapping	33
Figure 37.	Hybrid Mapping.....	34
Figure 38.	Wear-leveling.....	36
Figure 39.	Garbage Collection.....	37
Figure 40.	SSD Operating Current	40
Figure 41.	MTron PATA SSD Functional Block Diagram	41
Figure 42.	High Speed NAND	43
Figure 43.	Improving Endurance through Reduced Vt Margins.....	44
Figure 44.	Chameleon SSD Architecture.....	46
Figure 45.	Chameleon SSD Performance	46
Figure 46.	Effect of Block-level and Page-level Write Buffer.....	47
Figure 47.	Hybrid SSD Concept.....	47
Figure 48.	Data/Control Flows in Hybrid SSD	48
Figure 49.	SSD Workload Profile.....	49
Figure 50.	Circular Log Space in SLC NAND flash	49
Figure 51.	Hybrid SSD Endurance	50

Figure 52. HyperLink NAND SSD vs. Conventional SSD Architecture	51
Figure 53. Minimum SSD Capacity for 5 Year Product Life	55
Figure 54. Program Disturb	56
Figure 55. Read Disturb	57
Figure 56. Flash Error Rate Surface	58
Figure 57. SSD vs. HDD Bit Error Rates	58
Figure 58. ECC Selection	60
Figure 59. SSD vs. HDD Random IOPS.....	62
Figure 60. SSDs vs. HDDs in the Enterprise – Performance Characteristics	64
Figure 61. Enterprise SSD vs. HDD Average Capacity.....	64
Figure 62. SSDs vs. HDDs in PCs – Performance Characteristics.....	66
Figure 63. SSD Performance Trend	67
Figure 64. Notebook PC SSD vs. HDD Average Capacity	68
Figure 65. Desktop SSD vs. HDD Average Capacity	68
Figure 66. SSDs vs. HDDs in Low Cost Mobile PCs – Performance Characteristics	70
Figure 67. LC Mobile PC SSD vs. HDD Average Capacity	71
Figure 68. SSD vs. HDD Price Curve	72
Figure 69. HDD and SSD Landscape.....	75
Figure 70. SSD Patents by Type.....	78
Figure 71. SSD-related Patents by Company	79
Figure 72. Applications Write/Read Workload.....	86
Figure 73. Applications Sequential/Random Workload.....	86
Figure 74. Total Enterprise SSD Units Forecast.....	88
Figure 75. Total Enterprise SSD Revenue Forecast	88
Figure 76. Enterprise Storage Drive Units Forecast	89
Figure 77. Enterprise Storage HDD Unit Forecast	90
Figure 78. Enterprise Storage SSD Unit Forecast.....	91
Figure 79. Enterprise Storage SSD GB Forecast	91
Figure 80. Enterprise Storage SSD GB / Unit Forecast.....	92
Figure 81. Enterprise Storage SSD \$ / GB Forecast	92
Figure 82. Enterprise Storage SSD Revenue Forecast.....	93
Figure 83. Enterprise Server Units Forecast	94
Figure 84. Host Server-attached SSD Unit Forecast.....	95
Figure 85. Host Server-attached SSD GB Forecast	95
Figure 86. Host Server-attached SSD GB / Unit Forecast.....	96
Figure 87. Host Server-attached SSD \$ / GB Forecast	96
Figure 88. Host Server-attached SSD Revenue Forecast	97
Figure 89. Low Cost Mobile PC Unit Forecast	98
Figure 90. Endurance vs. SSD Capacity	99
Figure 91. Low Cost Mobile PC SSD Unit Forecast	100
Figure 92. Low Cost Mobile PC SSD GB Forecast.....	104
Figure 93. Low Cost Mobile PC SSD Revenue Forecast.....	104
Figure 94. Notebook PC Unit Forecast	105
Figure 95. Notebook PC SSD Unit Forecast	106
Figure 96. Notebook PC SSD GB Forecast.....	111
Figure 97. Notebook PC SSD Revenue Forecast	111
Figure 98. Desktop PC Unit Forecast.....	112
Figure 99. Desktop PC SSD Unit Forecast.....	113
Figure 100. Desktop PC SSD GB Forecast.....	115
Figure 101. Desktop PC SSD Revenue Forecast	115
Figure 102. Computing SSD Unit Forecast	116
Figure 103. Computing GB Forecast	116

Figure 104. Computing SSD Revenue Forecast 117

List of Tables

Table 1.	SSD Bill of Materials.....	24
Table 2.	ECC Trend.....	38
Table 3.	HLNAND SSD vs. Conventional SSD.....	52
Table 4.	SSD Capacity as a Function of Writes / Day.....	55
Table 5.	Enterprise Class SSD vs. HDD	63
Table 6.	PC-Class SSD vs. HDD	65
Table 7.	Interface Transfer Speeds	67
Table 8.	Interface Transfer Speeds	67
Table 9.	Low Cost Mobile PC SSD vs. HDD	69
Table 10.	SSD Chronology.....	73
Table 11.	Seagate's Patent Claims against STEC.....	80
Table 12.	Enterprise SSD vs. HDD Key Metrics	82
Table 13.	Video-on-Demand SSD TAM	84
Table 14.	Enterprise HDD:SSD Replacement Ratio	90
Table 15.	SSD NAND Flash Technology under Four Scenarios.....	99
Table 16.	LC Mobile PC SSD Capacity Unit Mix Forecast	101
Table 17.	LC Mobile PC SSD Capacity GB Mix Forecast.....	102
Table 18.	LC Mobile PC SLC SSD Price Forecast.....	102
Table 19.	LC Mobile PC MLC SSD Price Forecast.....	103
Table 20.	LC Mobile PC 3-bit per cell SSD Price Forecast.....	103
Table 21.	Notebook PC SLC SSD Capacity Unit Mix Forecast.....	107
Table 22.	Notebook PC SLC SSD Capacity GB Mix Forecast.....	108
Table 23.	PC SLC SSD Price Forecast.....	108
Table 24.	PC MLC SSD Price Forecast.....	109
Table 25.	PC SLC/3-bit per cell SSD Price Forecast.....	110
Table 26.	Desktop PC SSD Capacity Unit Mix Forecast.....	113
Table 27.	Desktop PC SSD Capacity GB Mix Forecast	114