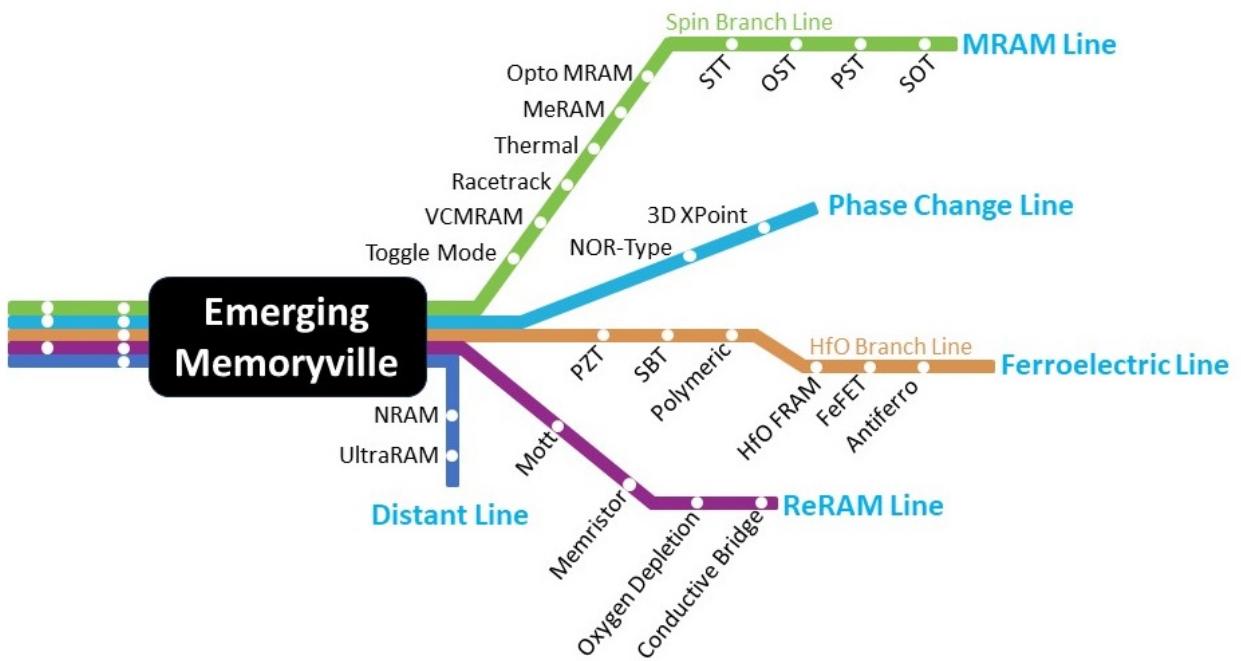


EMERGING MEMORIES BRANCH OUT



**COUGHLIN ASSOCIATES & OBJECTIVE
ANALYSIS**
August 2023

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CONTENTS

Contents	iii
Figures.....	1
Tables.....	6
Executive Summary	8
Introduction.....	10
Why Emerging Memories are Popular	14
Scaling Limits For Entrenched Technologies.....	14
3D NAND Flash Technologies.....	14
Future Flash Memories	19
3D DRAM.....	19
Embedded NOR and SRAM Scaling Challenges	21
Standalone NAND & DRAM Scaling Concerns.....	25
Technical Advantages.....	26
Emerging Memories for Radiation Tolerance	27
Alternatives to Using Emerging Memories	30
Potential Cost/GB Advantages	31
Which Applications want Emerging Memories First?.....	32
How a New Memory Layer Can Improve Computer Performance.....	33
How Persistence Changes the Memory/Storage Hierarchy	33
Changes in Computer Memory Usage.....	35
Standardizing The Persistent Memory Software Interface	37
Chiplets and PCIe.....	38
In-Memory Computing Possibilities.....	41
Fewer Constraints On MCU Programmers.....	42
Compute Express Link (CXL).....	43
The Crucial Importance Of The Economies Of Scale	46
How Scale Economies Undermined Intel’s “Optane” 3D XPoint PCM	49
Intel’s “Optane” 3D Crosspoint Memory Story.....	51
Optane Applications.....	52
Understanding Bit Selectors	55
Resistive RAM, ReRAM, RRAM, Memristor	64
ReRAM Device Function	65
Mott Devices	70
HP’s Memristor.....	71
Stacking ReRAM Arrays	72
ReRAM CMOS Integration	73
3D NAND Approach to ReRAM.....	75
ReRAM and Artificial Intelligence.....	75
Current ReRAM Status	77
Ferroelectric RAM, FeRAM, FRAM.....	80
FRAM Operation	82
Ferroelectric Cell Structures	83
Capacitor-Based Cell	84

FTJ, the Ferroelectric Tunnel Junction	86
FRAM Product Status	86
Ferroelectric Materials: PZT, BST, and HfO.....	87
FRAM Device Characteristics	91
3D FeFET FRAM	93
Antiferroelectrics	94
The Future of FRAM	95
Phase Change Memory (PCM)	98
3D XPoint Memory: Intel's Optane.....	99
Operation of PCM.....	99
Advantages and Disadvantages.....	103
PCM Applications.....	104
MRAM (Magnetic RAM), STT MRAM (Spin Transfer Torque MRAM)	105
MRAM	105
The Nine Basic MRAM Types	107
STT MRAM.....	109
How STT Works	116
STT Manufacture	118
STT Strengths & Weaknesses.....	120
Spin-Orbit Torque MRAM	125
MeRAM, An Alternative Spin Memory Device.....	127
Spintronic Photonic Memory	129
Racetrack Memory.....	130
MRAM in Artificial Intelligence	131
Other Emerging Memory Types	135
Carbon Nanotubes (CNT)	135
Van der Walls CNT Flash.....	136
Polymeric Ferroelectric RAM (PFRAM)	137
III-V Floating Gate "UltraRAM".....	138
Lithography	140
Multi-Patterning	140
Extreme UV (EUV) Technology	142
High Numerical Aperture EUV	144
EUV Challenges.....	146
Future Lithography	147
Nano-Imprint Lithography.....	147
3D Memory Circuit Design	152
3D Memory Circuit Approaches.....	152
Summary of Solid-State Memory & Storage Technologies	154
Emerging Memories and New Materials	158
Emerging Memory Process Equipment	159
MRAM and STT MRAM Process Equipment.....	161
Physical Vapor Deposition	164
Ion Beam and Plasma Etching	172
Photolithography (Patterning).....	182
Other Process Equipment.....	185

Device Testing	186
MRAM and STT MRAM Consortia.....	192
Phase-Change Manufacturing Equipment	192
Memory is Driving Semiconductor Capital Spending.....	194
Market Projections for MRAM.....	196
MRAM Scenario Estimates	202
Estimates of MRAM Capital Equipment Demand	209
Ion Beam Etching Equipment.....	210
Patterning Equipment.....	212
Magnetic Annealing Equipment	214
Physical Vapor Deposition Equipment.....	216
Test and Other Equipment	218
Summary of MRAM Equipment Demand.....	221
Emerging Memory Manufacturing Support.....	225
Company Information.....	226
Memory And Applications Companies & Organizations.....	226
3D Plus.....	226
4DS Memory.....	226
Adesto Technologies.....	227
Advanced Memory Semiconductor (AMS)	227
Advanced Memory Technology (AMT).....	227
Ambiq	227
Antaios	227
Arm	227
Avalanche Technology	227
BAE Systems	228
BeSang	228
CAES	229
CAO-SIP.....	229
CEA-Leti.....	229
Cerfe Labs	229
Chinese Academy of Sciences (中国科学院)	229
CIES	229
Ciyu.....	230
CNSE (College of Nanoscale Science and Engineering)	230
Cobham-Aeroflex	230
Crocus Technology	230
CrossBar.....	230
Cypress.....	230
Dialog Semiconductor	231
eMemory Technology	231
Eindhoven University of Technology (TU/e)	231
Ensurge Micropower.....	231
eVaderis	232
Everspin	232
Ferroelectric Memory Company	232

Fert Beijing Institute of Bei hang University.....	232
Frontgrade	233
Fujitsu Semiconductor	233
GigaDevice Semiconductor, Inc. (兆易创新)	233
Grandis	233
GREAT	233
Gyrfalcon Technology	234
Hikstor (驰拓科技)	234
HPE	234
Honeywell	235
IBM	235
imec	235
Institute of Microelectronics (Chinese Academy of Sciences).....	235
Infineon	236
Innostar (昕原半导体)	236
Innovation Memory (新忆科技).....	236
Inston.....	236
Integrated Device Technology (IDT).....	237
Intel	237
Intermolecular	237
IntrinSic.....	237
ITRI	237
Jiangsu Advanced Memory (江苏时代芯存半导体)	238
Kioxia.....	238
Knowm.....	238
Lapis Semiconductor	239
Leti	239
Macronix	239
Merck	239
Microchip	239
Micron Technology.....	239
Microsemi	240
Micross.....	240
NaMLab	240
Nantero.....	240
National Tsing Hua University	241
NEC.....	241
Nextorage.....	241
Numem.....	241
Numonyx.....	241
Nuvoton.....	241
NVE	242
NXP	242
Ovonyx.....	242

Panasonic	242
Qualcomm.....	242
Rambus	243
Ramtron.....	243
Reliance Memory (合肥睿科微电子有限公司)	243
Renesas Electronics	243
ROHM	244
Samsung Semiconductor.....	244
SanDisk.....	244
Seagate Technology	245
Shanghai Ciyu Information Technologies (SCIT, 上海磁宇/磁宇信息).....	245
SiEn (QingDao) Integrated Circuits (芯恩(青岛)集成电路)	245
SK hynix	245
Sony Corporation.....	246
Spin-Ion.....	246
Spin Memory	246
SPINTEC	247
Spin Orbitronics	247
Stanford University.....	247
STMicroelectronics.....	247
SUNY (State University of New York).....	248
sureCore	248
Symetrix.....	248
TDK	248
Teledyne e2v Semiconductors	248
Texas Instruments	248
TMC.....	249
Tohoku University	249
Toshiba.....	249
Truth Memory Tech, Corp (TMC, 致真存储).....	249
TU/e	249
University at Albany College of Nanoscale Science and Engineering (CNSE)....	249
Unidym	249
Veevx	249
Weabit Nano	250
Western Digital	250
Winbond.....	250
XTX Technology (芯天下).....	251
Semiconductor Foundries	251
Crocus Nanoelectronics	251
DB HiTek.....	251
GlobalFoundries.....	251
Hangzhou HFC Semiconductor (杭州积海半导体有限公司)	252
Samsung.....	252

SilTerra	252
SkyWater Technology	252
SMIC (中芯)	253
Tower Semiconductor	253
TPSCo	253
TSMC	253
UMC	254
Capital Equipment Manufacturers	254
Accretech	254
ANELVA	254
Applied Materials	254
ASM	254
ASML	255
Bruker	255
Canon	255
Canon-ANELVA	255
CAPRES A/S	256
Hitachi High Technology	256
Hprobe	256
Integral Solutions, Inc. (ISI)	256
Jusung Engineering	257
Keysight Technologies	257
KLA Tencor	257
Lake Shore	257
Lam Research	257
Leuven Instruments (鲁汶仪器)	257
MagOasis	258
MicroSense	258
Nanomagnetics Instruments	258
Neoark	258
Nikon	258
Onto Innovation	258
Oxford Instruments	259
Plasma Therm	259
SHB	259
Singulus Technologies	259
Smart Tip	259
Tokyo Electron	259
Tokyo Seimitsu	259
Ulvac	260
Veeco	260
Methodology	261
Further Reading	262
Authors	263
Tom Coughlin	263
Jim Handy	263

FIGURES

Figure 1. Memory Density and Power Requirements by Application Category	10
Figure 2. Solid State Memory/Storage Technologies	11
Figure 3. 3D NAND Flash Memory Topology.....	15
Figure 4. Toshiba's BiCS and Samsung's TCAT 3D NAND Structures	16
Figure 5. Cost of Transition from One NAND Manufacturing Process to the Next	18
Figure 6. Projected NAND Flash Chip Technology Roadmap.....	19
Figure 7. Intel's Antiferroelectric DRAM.....	20
Figure 8. SRAM Cell Sizes Shrink More Slowly Than Processes, Causing f^2 to Balloon	22
Figure 9. Historically, SRAM Caches Scaled in Proportion to Processor Logic	23
Figure 10. SRAM in Future Processes Will Scale More Slowly than Processor Logic ..	24
Figure 11. SRAM Cell Size vs. Process for Intel, Samsung, and TSMC	25
Figure 12. Cross Section of a Flash Memory Bit Cell.....	28
Figure 13. An Alpha Particle Drags Electrons Out of the Floating Gate	29
Figure 14. Infineon's Vision of Future External Flash Topologies	30
Figure 15. Memory/Storage Price per Gigabyte vs. Performance	34
Figure 16. Progression of Storage Technologies with Nonvolatile Solid-State Storage ..	36
Figure 17. Solid-State Storage Latency Sources.....	37
Figure 18. Gordon Moore's Estimation of Contributions from Transistor Dimensions, Die Size, and Circuit Cleverness	38
Figure 19. Die Sizes Over Time	39
Figure 20. AMD EPYC 7702 with I/O Chiplet Surrounded by Eight Core Complex Chiplets	40
Figure 21. ReRAM System on Chip	42
Figure 22. Intel's DDR-T Interface	44
Figure 23. Large CXL-Based System with Eight Hosts Sharing Two Memory Pools....	45
Figure 24. NAND Flash Prices Crossed Below DRAM in 2004.....	47
Figure 25. 2004 NAND Gigabyte Shipments Reached 1/3rd That of DRAM	48
Figure 26. Estimated Intel 3D XPoint Quarterly Losses	50
Figure 27. Estimated Optane Revenues and Petabyte Shipments.....	51
Figure 28. Intel's View of the Memory-Storage Hierarchy	53
Figure 29. Redis Virtual Machine Count vs. Memory Size.....	54
Figure 30. Bit Selectors - 3-Terminal (Left) 2-Terminal (Right)	56
Figure 31. Overhead View of a Simple Crosspoint Array	57
Figure 32. Reading When One Bit Is in a Low-Resistance State	57
Figure 33. Sneak Paths Occur when Multiple Bits are in a Low Resistance State	58
Figure 34. Space Penalty of a 3-Terminal Selector	59
Figure 35. Bidirectional Diode Selector	60
Figure 36. A 1TnR Selector Configuration.....	61
Figure 37. 3D Crosspoint Array Stacking.....	62
Figure 38. Stacked Crosspoint Memory Array	62
Figure 39. ReRAM Filament Cell Conduction and Switching	65

Figure 40. ReRAM Scaling.....	66
Figure 41. ReRAM Resistance Scaling	66
Figure 42. TaOx ReRAM Device	67
Figure 43. TaOx Oxygen Vacancy Structure of eMemory Cell	68
Figure 44. Current Levels and Voltages for ReRAM Switching.....	68
Figure 45. Cross-section Photo of Weabit Nano ReRAM.....	69
Figure 46. CeRAM Cell vs. ReRAM Cell	70
Figure 47. Where the Memristor Fits in the World of Passive Components	71
Figure 48. ReRAM Stacked Crosspoint Array	72
Figure 49. ReRAM CMOS Integration.....	74
Figure 50. Two-Mask ReRAM Element in Tungsten Vias	74
Figure 51. 3D ReRAM Structure/Process.....	75
Figure 52. A Simplified View of a Neural Network.....	76
Figure 53. Early Ferroelectric Memory - 1955 Bell Labs 256-Bit Device	81
Figure 54. Hysteresis Curve of Ferroelectric Memory	82
Figure 55. FRAM Perovskite Displacement.....	83
Figure 56. Topology of FRAM, FeFET, and Ferroelectric Tunnel Junction.....	84
Figure 57. FeFET Cross Section.....	85
Figure 58. FeFET Transistor.....	85
Figure 59. Publication Count for FeFET Research Papers	88
Figure 60. Amorphous, Crystalline, and Ferroelectric Hafnium Oxide	89
Figure 61. Typical Dimensions of PZT and HfO Capacitors	90
Figure 62. Memory Properties of Ferroelectric Hafnium Oxide	91
Figure 63. FRAM Planar Cell Structure	93
Figure 64. 3D Hafnium Oxide FRAM Built Using 3D NAND Techniques	94
Figure 65. Antiferroelectric Hysteresis Loop	95
Figure 66. SK hynix' Ferroelectric 3D NAND flash	97
Figure 67. Crosspoint Memory Using PCM Cells.....	100
Figure 68. Characteristics of the Read, Write and Erase Cycle for PCM Materials....	101
Figure 69. PCM Memory Cell	102
Figure 70. Cross Section of PCM Cell	102
Figure 71. STMicroelectronics' Transistor-Selected PCM Cell	103
Figure 72. Basic Cell Diagram for Toggle MRAM.....	106
Figure 73. Toggle MRAM Architecture	107
Figure 74. Die Photograph of Everspin 1Gb STT MRAM.....	110
Figure 75. GlobalFoundries' Roadmap for Embedded MRAM	112
Figure 76. Samsung's MRAM In-Memory Processing 64X64 array Device.....	114
Figure 77. TSMC's Embedded MRAM/RRAM Plans	115
Figure 78. Parallel to Antiparallel Switching	117
Figure 79. Spin Transfer Torque Operation.....	117
Figure 80. In-Plane and Perpendicular Magnetic Tunnel Cells	118
Figure 81. STT MRAM Cell Structure	118
Figure 82. Everspin STT MRAM Stack Structure.....	119
Figure 83. Everspin STT MRAM Produced on 28nm GlobalFoundries Process.....	119
Figure 84. Comparing NOR vs. STT MRAM Write Energy.....	121
Figure 85. STT MRAM Current Operation	122

Figure 86. Reading a Multi-Bit MRAM Cell.....	122
Figure 87. DRAM, NAND Flash and STT MRAM Price vs. Latency.....	123
Figure 88. STT MRAM Cross Section	124
Figure 89. Bit Dimensions of Ideal MRAM, DRAM, Planar NAND Flash and HDD .	124
Figure 90. STT MRAM Embedded Memory	125
Figure 91. STT-MRAM vs. SOT-MRAM.....	126
Figure 92. MeRAM Device Structure.....	128
Figure 93. MeRAM Stack.....	128
Figure 94. IBM's Racetrack Memory - Conceptual Diagram.....	130
Figure 95. Laboratory Embodiment of IBM's Racetrack Memory.....	131
Figure 96. Gyrfalcon AI Accelerator with MRAM	132
Figure 97. Numem DNN Device with MRAM for Space Applications.....	132
Figure 98. Ambiq Apollo 4 IoT SoC	133
Figure 99. Ambiq Apollo 4 Blue 16Mb Memory Array in a Fitbit Lux Fitness Band..	134
Figure 100. Sony eMRAM Buffer Memory for CIS	134
Figure 101. CNT Fabric.....	136
Figure 102. PFRAM 3-Layer Polymeric Memory.....	138
Figure 103. Profile of University of Lancaster UltraRAM bit cell.....	139
Figure 104. Original Single-Patterned Features.....	141
Figure 105. Clad the Sides of the Original Pattern	141
Figure 106. Remove the Original Pattern. The Remaining Cladding is a Doubled Pattern	141
Figure 107. Clad the Sides of the Doubled Pattern.....	142
Figure 108. Remove the Doubled Pattern. The Remaining Cladding is the Quadrupled Pattern	142
Figure 109. Light Spectrum	143
Figure 110. EUV Scanning Lithographic Exposure System	143
Figure 111. imec/ASML hNA EUV Roadmap.....	145
Figure 112. ASML hNA EUV Beam Path.....	146
Figure 113. Nanoimprint Process	149
Figure 114. Nanoimprint Depressions	150
Figure 115. Fluid Dispense Process.....	150
Figure 116. Largest Memory Densities Presented at IEEE Research Conferences, 2001- 2022.....	155
Figure 117. Future Memory/Storage Hierarchy.....	157
Figure 118. Elements Used in New Memories	158
Figure 119. Emerging Memory Cell Structure Comparison.....	159
Figure 120. MRAM Memory Cell	161
Figure 121. MRAM Cross-Section	162
Figure 122. MRAM Manufacturing Process Flow	163
Figure 123. Key MRAM Process Equipment	163
Figure 124. Applied Materials CMP System.....	166
Figure 125. Applied Materials Endura Clover Platform.....	166
Figure 126. Canon Anelva EC7800 PVD Tool	167
Figure 127. Canon Anelva NC7900 PVD Tool.....	168
Figure 128. Singulus Timaris II PVD Cluster Tool Platform.....	168

Figure 129. Singulus PVD Cluster Tool Platforms	169
Figure 130. Tokyo Electron Exim PVD Cluster Tool Platform	170
Figure 131. Ulvac ENRON EX W300 Multilayer Thin Film Deposition System	171
Figure 132. Veeco Nexus IBD Ion Beam Deposition System.....	172
Figure 133. A Three Grid Ion Beam Extraction System	173
Figure 134. MTJ Etching Process.....	173
Figure 135. Applied Materials Centura	174
Figure 136. Canon Anelva Nc8000 Ion Beam Etch Machine	175
Figure 137. Hitachi High Technology E-600/8000 Nonvolatile Etch System	176
Figure 138. Lam Research Semiverse	178
Figure 139. Lam Research Kiyo Ion Beam Etching Chamber	178
Figure 140. Oxford Instruments Ionfab 300 IBE System.....	179
Figure 141. Plasma Therm QuaZar Ion Beam Etch and Deposition System.....	180
Figure 142. Ulvac NE-7800H Non-Volatile Material Etching Tool	181
Figure 143. Veeco Nexus IBE-420I Ion Beam Etching System.....	181
Figure 144. ASML Deep UV Photolithography Tool	183
Figure 145. Nikon Photolithographic Product Lines	183
Figure 146. Canon Lithographic Stepper Products.....	184
Figure 147. Tokyo Electron MRT300 Magnetic Annealing Tool	185
Figure 148. ISI WLA 5000 Wafer Level Quasi-Static Tester	187
Figure 149. HProbe 3D High Magnetic Field Wafer Probe	188
Figure 150. Keysight Technology NX5730A MRAM Test Platform	189
Figure 151. MicroSense (KLA/Tencor) Polar Kerr System for Perpendicular STT MRAM.....	190
Figure 152. Atomic Force Microscopy Concept (AFM)	191
Figure 153. Applied Materials Endura Impulse for PCM and ReRAM	193
Figure 154. SEMI's Wafer Fab Equipment Spending History and Forecast	194
Figure 155. Standalone Memory Prices 2022-2033	197
Figure 156. Standalone Memory Annual Petabyte Shipments, 2022-2033.....	199
Figure 157. Standalone Memory Annual Revenues 2022-2033	201
Figure 158. Three Scenarios for Standalone MRAM Annual Wafer Consumption 2022- 2033.....	203
Figure 159. Three Scenarios for Embedded MRAM Annual Wafer Consumption 2022- 2033.....	204
Figure 160. Three Scenarios for Combined MRAM Annual Wafer Consumption 2022- 2033.....	205
Figure 161. Three Scenarios for Combined MRAM Petabyte Production 2022-2033..	206
Figure 162. Three Scenarios for Combined MRAM Revenues 2022-2033	207
Figure 163. Capital Equipment Estimate Process Flow.....	210
Figure 164. Three Scenarios of MRAM Ion Beam Etching Equipment Spending 2022- 2033.....	212
Figure 165. Three Scenarios of MRAM Patterning Equipment Spending 2022-2033..	214
Figure 166. Three Scenarios of MRAM Magnetic Annealing Equipment Spending 2022- 2033.....	216
Figure 167. Three Scenarios of MRAM Physical Vapor Deposition Equipment Spending 2022-2033	218

Figure 168. MRAM Combined Test and Other Equipment Baseline Spending Estimates 2022-2033	220
Figure 169. Three Scenarios of MRAM Test and Other Equipment Spending 2022-2033	221
Figure 170. MRAM Combined Baseline Equipment Spending Estimates 2022-2033 .	223
Figure 171. Three Scenarios of MRAM Total Equipment Spending 2022-2033	224

TABLES

Table 1. Solid State Memory Technology Comparison.....	35
Table 2. UCIE Key Members	41
Table 3. DRAM and SLC NAND Die Sizes.....	46
Table 4. Summary of Emerging Memory Technologies	156
Table 5. MRAM Process Equipment Vendors	164
Table 6. Tokyo Electron Magnetic Annealing Product Line-Up.....	186
Table 7. Historical Equipment Spending by Region (\$B)	195
Table 8. Standalone Memory Prices, 2022-2033 (\$/GB)	197
Table 9. Standalone Memory Annual Petabyte Shipments, 2022-2033	198
Table 10. Assumptions for Baseline Standalone MRAM Model	200
Table 11. Standalone Memory Annual Revenues 2022-2033 (\$M)	201
Table 12. Three Scenarios for Standalone MRAM Annual Wafer Consumption 2022-2033.....	202
Table 13. Three Scenarios for Embedded MRAM Annual Wafer Consumption 2022-2033.....	203
Table 14. Three Scenarios for Combined MRAM Annual Wafer Consumption (Units) 2022-2033	205
Table 15. Three Scenarios for Combined MRAM Production 2022-2033 (Petabytes).....	206
Table 16. Three Scenarios for Combined MRAM Revenues 2022-2033 (\$M)	207
Table 17. MRAM Ion Beam Etching Equipment Baseline Unit Shipment Estimates 2022-2033	211
Table 18. MRAM Ion Beam Etching Equipment Baseline Spending Estimates 2022-2033 (\$M)	211
Table 19. MRAM Patterning Equipment Baseline Unit Shipment Estimates 2022-2033	213
Table 20. MRAM Patterning Equipment Baseline Spending Estimates 2022-2033 (\$M)	213
Table 21. MRAM Magnetic Annealing Equipment Baseline Unit Shipment Estimates 2022-2033	215
Table 22. MRAM Magnetic Annealing Equipment Baseline Spending Estimates 2022-2033.....	215
Table 23. MRAM Physical Vapor Deposition Equipment Baseline Unit Shipment Estimates 2022-2033.....	217
Table 24. MRAM Physical Vapor Deposition Equipment Baseline Spending Estimates 2022-2033	217
Table 25. MRAM Test and Other Equipment Baseline Unit Shipment Estimates 2022-2033 (\$M)	218
Table 26. MRAM Test & Other Equipment Price Estimates 2022-2033	219
Table 27. MRAM Test & Other Equipment Baseline Spending Estimates 2022-2033	219
Table 28. MRAM Combined Equipment Baseline Unit Shipment Estimates 2022-2033	222
Table 29. MRAM Combined Equipment Baseline Spending Estimates 2022-2033 (\$M)	222

Table 30. Emerging Memory Foundry Offerings 225

EXECUTIVE SUMMARY

Flash memory (NAND and NOR), DRAM, SRAM, and other popular memory technologies are facing potential technology limits to their continued improvement. This has resulted in intense efforts to develop new memory technologies. Most of these new technologies are nonvolatile memories, which can be used for long-term storage or to provide a memory that retains information when powered down. Nonvolatile memories offer advantages for battery and ambient powered devices and also for energy savings in data centers.

PCM, ReRAM, FRAM, Toggle MRAM, and STT MRAM are emerging memories addressed in this report, as well as a variety of less mainstream technologies such as carbon nanotubes. Based upon the level of current development and the characteristics of resistive RAM (ReRAM) technologies, they may be a potential replacement for flash memory. However, NAND flash memory will continue to undergo several generations of improvement that will be implemented before a replacement is required. A transition from NAND flash to some other technology will likely not occur until the next decade, at the earliest.

Intel's recent termination of its Optane 3D XPoint campaign has shown that the economies of scale play perhaps an even larger role in the emerging memories market than we had thought. The report devotes a number of pages to explain the impact of the economies of scale on both NAND flash and Optane to come to the conclusion that wafer volume must approach 10% of the volume of a competing technology in order to reach cost parity. Intel's full disclosure of the losses attributable to its Optane technology were in line with earlier Objective Analysis estimates.

Magnetic RAM (MRAM) and spin transfer torque RAM (STT MRAM) are starting to replace some NOR flash and SRAM and could possibly displace some DRAM within the next few years, well before ReRAM replaces NAND flash memory. The rate of development and increasing product volume in STT MRAM and other MRAM technologies will gradually result in lower prices. The attractiveness of replacing volatile memory with high speed and high endurance nonvolatile memory make these technologies very competitive, assuming that their volume increases to reduce production costs (and thus purchase prices).

Ferroelectric RAM (FRAM) and some ReRAM technologies have some niche applications and with the use of HfO FRAM the number of niche markets available for FRAM could increase.

Moving to a nonvolatile solid-state main memory and cache memory will reduce power usage directly as well as enable new power saving modes, provide faster recovery from power off and enable more stable computer architectures that retain their state even when power is off. Eventually spintronic technology, that uses spin rather than current for logic functions, could be used to make future microprocessors. Spin-based logic combined with spin-based memory could enable very efficient in-memory computing. Several emerging memory technologies are also being used in neuromorphic computing experiments.

The use of a nonvolatile technology as an embedded memory combined with CMOS logic has great importance in the electronics industry. NOR flash in embedded devices reached its scaling limit at 28nm, and is being replaced with one of these new non-volatile technologies (especially MRAM and ReRAM). As a replacement for a multi-transistor SRAM, STT MRAM could dramatically reduce the number of memory transistors and thus provide a low cost, higher-density solution. A number of enterprise and consumer devices currently use MRAM, to act as an embedded cache memory, and this trend will continue.

Because of the compatibility of MRAM and STT-RAM processes with conventional CMOS processes, these memories can be built directly on top of CMOS logic wafers. Flash memory doesn't have the same compatibility with conventional CMOS. The power savings of nonvolatile and simpler Toggle MRAM and STT MRAM when compared with SRAM is significant. As MRAM \$/GB costs approach those of SRAM, this replacement could create significant market expansion.

It is projected that total MRAM and STT MRAM baseline annual shipping capacity will rise from an estimated 133TB in 2022 to 4.56EB in 2033. Total MRAM and STT-RAM baseline revenues are expected to increase from \$279M in 2022 to about \$59.2B by 2033.

Much of this revenue gain will be at the expense of SRAM, NOR flash and some DRAM, although STT-RAM is developing its own special place in the pantheon of shipping memory technologies.

The demand for MRAM and STT-MRAM will drive demand for capital equipment to manufacture these devices. While MRAM and STT-MRAM can be built on standard CMOS circuits supplied by large semiconductor fabricators, MRAM and STT MRAM do require specialized fabrication equipment for the MRAM layers that is similar to or the same as that used in manufacturing the magnetic read sensors in hard disk drives.

The increasing demand for nonvolatile memory based upon MRAM and STT MRAM will cause total manufacturing equipment revenue used for making the MRAM devices to rise from an estimated \$55.1M in 2022 to between \$302M to \$4.3B by 2033 with a baseline projected spending of \$2.2B.

INTRODUCTION

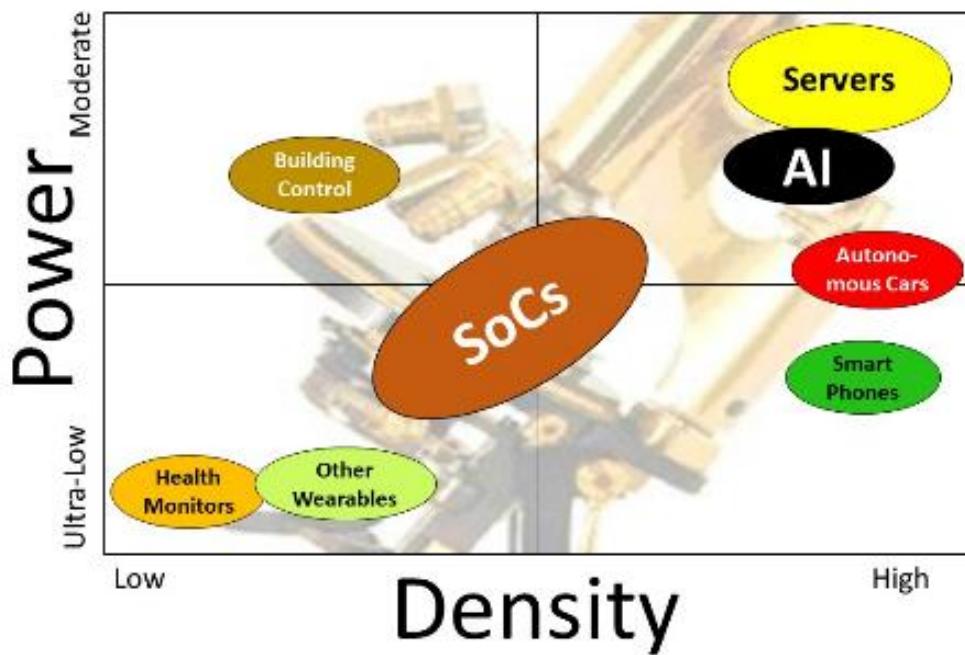
As the Internet of Things builds out, and as a growing number of devices make new measurements of data that was previously unmeasured, the world's data processing needs will grow exponentially.

This growth will not be matched with increases in communication bandwidth, despite the adoption of new wireless standards like 5G. In response to this mismatch, an increasing amount of processing will be performed at the edge, particularly in single-chip devices whose power consumption must be kept in check. This is the application that promises to benefit the most from today's nascent adoption of emerging memory technologies.

IoT endpoints need to process and interpret this data, often in near real time. Combine this with the amount of data that must be stored and processed to train various types of artificial intelligence (AI) models, and the result is a great increase in demand for memory and storage.

Figure 1 provides a rough idea of the memory density and power consumption needs of a number of modern application types.

Figure 1. Memory Density and Power Requirements by Application Category



Source: Objective Analysis, 2018

In order to make this information useful, our ability to process and interpret this data must also increase—the use of fast nonvolatile memory devices will be a key element in making this vast amount of information useful. Improved processing performance requires a good match of processor speed with communication bus speeds as well as memory data rates. It also requires latencies that are adequate for the application being processed.

More advanced semiconductor processing technologies will also play a key role in the transition to emerging memories, as established memory technologies like NOR flash and SRAM fail to keep pace with the relentless march of Moore's Law.

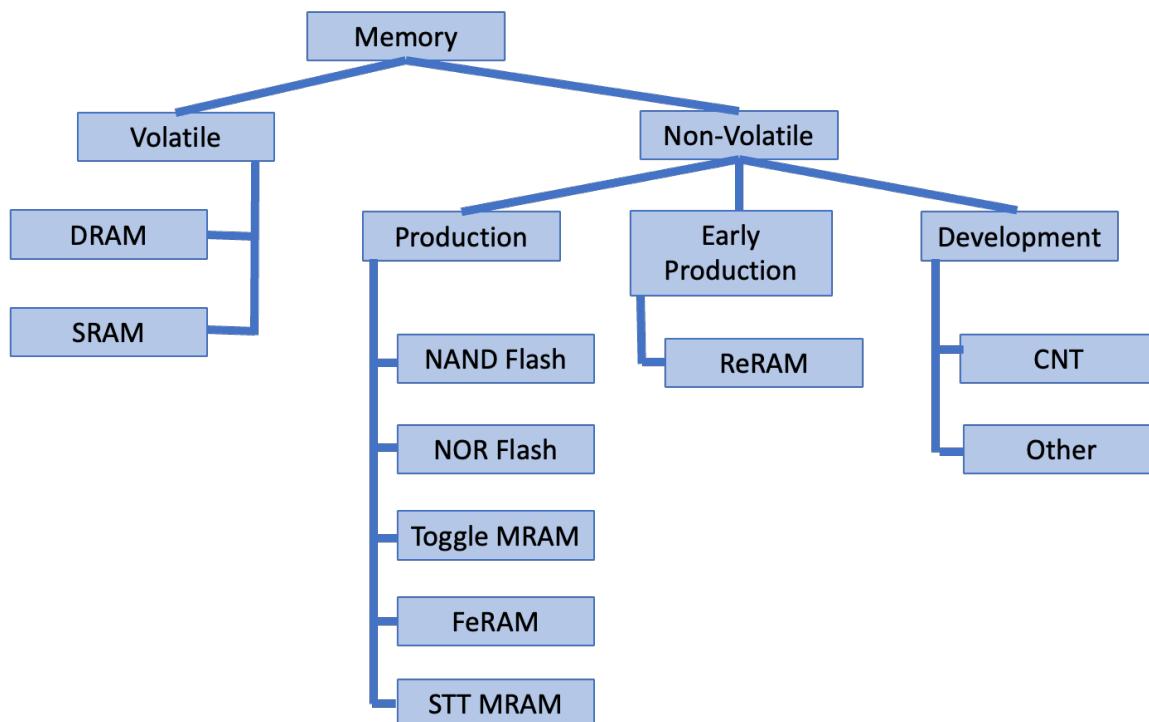
This report investigates the technologies associated with solid-state nonvolatile memories and evaluates each from the viewpoint of competition with current volatile memories, magnetic hard disk drives and flash memories.

There are numerous emerging solid-state nonvolatile memory technologies described in the literature, some rather old, while others are more recent. Some products such as ferroelectric random-access memory (FRAM), phase change RAM (PCM) and toggle and STT magnetic RAM (MRAM) are available as low to moderate density memory or storage products. Other technologies including spin-orbit torque MRAM and resistive RAM (ReRAM) are in earlier stages of pilot or production ramps. Technologies such as carbon nanotube RAM (NRAM) are still primarily laboratory demonstrations.

The move to emerging technologies is not governed simply by technical issues. Intel's recent foray into the emerging memory business with its Optane brand of PCM "3D XPoint" memory has proven that the economies of scale play a role in a new technology's adoption that cannot be ignored.

This report discusses the leading solid-state memory and storage technologies shown in Figure 2.

Figure 2. Solid State Memory/Storage Technologies



Source: Coughlin Associates, 2023

The following emerging memory technologies are discussed in this report:

1. MRAM: Memories that use a magnetic effect
2. PCM: Memories based on thermal effects
3. ReRAM: Memories that use ionic effects
4. FRAM: Electric field driven memories
5. New nonvolatile technologies such as Carbon Nanotube memories

This report addresses the characteristics of each nonvolatile technology from the following properties:

1. Compatibility with CMOS process and structure
2. Present commercial state of the technology
3. Reliability and/or endurance
4. Cost
5. Density
6. Performance
7. Ultimate limits

Two fundamental application types of emerging memories are examined in this report. The first is a standalone memory chip. Flash memory chips are an example of such a technology, as are DRAM chips. The second is adding an emerging memory within a logic chip like a microcontroller, ASIC, or SoC (system-on-a-Chip). These are often called embedded applications.

Note that the use of NAND flash memory as an embedded memory within a logic chip necessitates a significant variation to a standard CMOS process, which can multiply its cost. As a consequence, NAND flash is not used for internal memories in logic devices. NOR flash memory can be compatible with CMOS for an on-chip embedded memory. Similarly, DRAM is far less commonly found embedded in logic than is SRAM, its logic-friendly counterpart.

The report provides some details on the manufacture of MRAM products which are ramping up in volume to compete with SRAM, NOR and DRAM as a nonvolatile microprocessor memory. We will also point out what drives memory adoption and discuss why one memory can come to displace another.

The report then presents the Coughlin Associates analysis of MRAM production tool technologies and demand for these tools under a variety of scenarios, and the characteristics of capital equipment used for MRAM manufacturing. This demand estimate is based on the best-case of the above scenarios for MRAM market acceptance. We use this to project the capital equipment demand to produce MRAM from 2022-2033. We also discuss the implications for other nonvolatile technologies such as FRAM and ReRAM.

The report finishes with a listing of over 100 companies involved in various emerging memory technology development, production, and capital equipment.

The report presents data collected through careful interviews participants on all sides of the emerging memory market: Developers, vendors, licensors and licensees, tool makers, foundries, etc. Data was collected by Coughlin Associates and Objective Analysis via field interviews and at trade conferences and seminars. Other historical data was gathered

from a wide variety of sources by the authors. Forecast data has been derived from primary and secondary sources, along with Objective Analysis' highly-regarded trend analysis of memory chip pricing and supply/demand dynamics. Capital spending reported here is an estimate since this is an emerging market. Conference attendance and extensive reading of widespread sources provided insight in technical areas. In certain cases, analyst judgment was called upon to expand upon the data that was available through these sources.

During reviews we were directed to lectures, interviews, and articles to obtain information concerning forecasts, expected technology directions, and future requirements. The authors wish to express our thanks to all colleagues who contributed their knowledge and insights to us as a valuable service to the storage and memory industry.

Not all of the detailed data that were gathered were included. As usual, if further questions or additional information is required, please contact the authors. The authors are also available to provide or develop additional information, on a project basis, (with due regard for the confidentiality of our sources.)

AUTHORS

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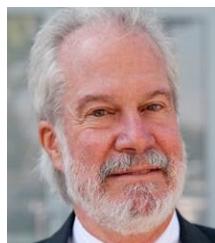


Tom Coughlin has worked for over 40 years in the data storage industry and is President of Coughlin Associates, Inc. He has over 500 publications and six patents and is a frequent public speaker on storage and memory topics. Tom is active with the IEEE, SMPTE, SNIA, and other professional organizations. Dr. Coughlin is an IEEE Fellow and HKN member. He is co-chair of the iNEMI Mass Storage Technical Working Group, Education Chair for SNIA CSMI, Past-President of IEEE-USA and a board member of the IEEE Consultants Network of Silicon Valley. Tom is the 2023 IEEE President Elect.

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Jim Handy



Jim Handy, a widely recognized semiconductor analyst, comes to Objective Analysis with over 30 years in the electronics industry including over 20 years as an industry analyst for Dataquest (now Gartner), Semico Research, and Objective Analysis. His background includes marketing and design positions at market-leading suppliers including Intel, National Semiconductor, and Infineon.

Mr. Handy is a member of the Storage Networking Industry Association (SNIA) Compute, Memory, and Storage Initiative (SSSI). He is also a Leader in the GLG Councils of Advisors, and serves on the Advisory Boards of the Flash Memory Summit. He has served as a member of the Mass Storage Technical Working Group of the International Electronics Manufacturing Initiative (iNEMI). He is the author of three blogs covering memory chips (www.TheMemoryGuy.com), SSDs (www.TheSSDguy.com), and semiconductors for the investor (www.Smartkarma.com and formerly blogs.Forbes.com/JimHandy). He contributes from time to time to a number of other blogs and professional journals.

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