The Impact of Areal Density and Millions of Square Inches (MSI) of Produced Memory on Petabyte Shipments of TAPE, NAND Flash, and HDD Storage Class Memories

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Abstract—**Increases in annual petabyte (PB) shipments for storage class memories (SCM) are driven by both increases in areal density and increases in manufacturing capacity. Increases in areal density tend to reduce cost per bit while increases in manufacturing capacity are cost neutral or slightly increase cost per bit. This paper surveys the last five years of PB shipments, areal density, revenue, and cost per bit for magnetic tape (TAPE), hard disk drives (HDD), and NAND flash to study manufacturing and cost trends for storage class memories. First, using the five year data for PB shipments and areal density values for TAPE, HDD and NAND flash, this paper applies a manufacturing measure used by semiconductors, millions of square inches or MSI of produced memory, to TAPE, HDD, and NAND flash in order to compare manufacturing requirements for these three SCM technologies. The MSI calculations shows for HDD and NAND, with slowing areal density increases, that manufacturing investments will be required for sustaining PB shipment growth while for TAPE modest investment in manufacturing capacity is required. The MSI calculations also show that the cost of NAND replacing HDD is prohibitive based simply on present day manufacturing capacity and show that for HDD to adopt processing requirements for patterned media, the next proposed areal density improvement for HDD, would require significant manufacturing investments. Second, using the five year data for PB shipments and revenue for TAPE, HDD, and NAND flash, trends in cost per bit for the SCM technologies can be determined and related to both technology innovations, i.e. lithography for NAND flash and predictable areal density increases for TAPE, and to external market factors, i.e. industry consolidation for HDD and mobile computing for NAND flash. Lastly, while 2012 PB shipments for TAPE, HDD, and NAND flash totaled 430,000 PB, dominated by HDD with 380,000 PB, perceived information creation in 2012 was over 1,300,000 PB, posing the question to SCM manufacturers as to how information is stored in today's environment.**

Keywords—Magnetic Disk Recording; Magnetic Tape Recording; Solid State Memories; Manufacturing Technology

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I. INTRODUCTION

Three main memory technologies used for storage class memory applications are hard disk drives (HDD), magnetic tape (TAPE), and NAND flash components in solid state drives (SSD). These three technologies are facing increasing challenges to continue to deliver increased device capacity at decreased cost per bit in order to meet the growing information generation demands in petabytes (PB) which are estimated to be increasing at ≥50% per year [1]. This paper examines the metrics for achieving increased device capacity or storage density from the perspectives of areal density, local volumetric density, and final component density. This paper examines the metrics for worldwide PB shipments for these three technologies using estimates of manufacturing capacity based on the millions of square inches (MSI) or surface area of memory shipped.

Table I shows the last 5 year history (2008 to 2012) of the growth of memory shipments for HDD, NAND, and TAPE. For this table, HDD units are drives, NAND units are 2 GB chips, and TAPE units are cartridges. For the purposes of this paper, TAPE data includes only the linear tape open shipments (LTO). Public data are not available for company specific enterprise shipments which could likely be estimated at ~20% of the LTO market. Data for Table I are available from a variety of sources [2, 3, 4].

Two comments are appropriate. First, comparisons of NAND and HDD with TAPE must be made in the context that TAPE has no consumer base while HDD and NAND gain much of their economies of scale from large consumer applications, e.g. PCs and digital imaging. For example, for 2011, while LTO TAPE enterprise and archival applications were 17,800 PB, it is estimated that enterprise HDD applications were 50,000 PB and NAND enterprise applications were estimated at 4,000,000 256 GB SSD drives or 1,000 PB. Second, TAPE, for the LTO data used in Table I, has a granular product introduction strategy so over the past

Table I
Storage Memory Growth (2008--2012)

	YE 2008	YE 2009	YE 2010	YE 2011	YE 2012
HDD					
Units (HDDs millions)	540	557	652	620	577
PB Shipped (PB)	125000	200000	330000	335000	380000
Areal Density (Gb/in²)	380	530	635	750	750
Revenue ($ billions)	34.0	34.0	33.0	33.5	37.5
$/GB Shipped	0.272	0.170	0.100	0.100	0.100
NAND					
Units (2GBs millions)	1500	2715	5232	9326	14000
PB Shipped (PB)	3000	5430	10464	18600	28000
Areal Density (Gb/in²)	200	280	330	550	550
Revenue ($ billions)	10.0	12.1	18.5	21.5	22.0
$/GB Shipped	3.33	2.23	1.77	1.16	0.78
LTO TAPE					
Units (Cart. millions)	20	24	25	25	22.7
PB Shipped (PB)	10400	12165	15300	17800	19500
Areal Density (Gb/in²)	0.9	0.9	1.2	1.2	1.2[1]
Revenue ($ billions)	1.0	0.7	0.7	0.7	0.62
$/GB Shipped	0.093	0.061	0.046	0.038	0.032

1. LTO6 product introduction was late 2012 and the associated areal density of 2.1 Gbit/in² was not included.

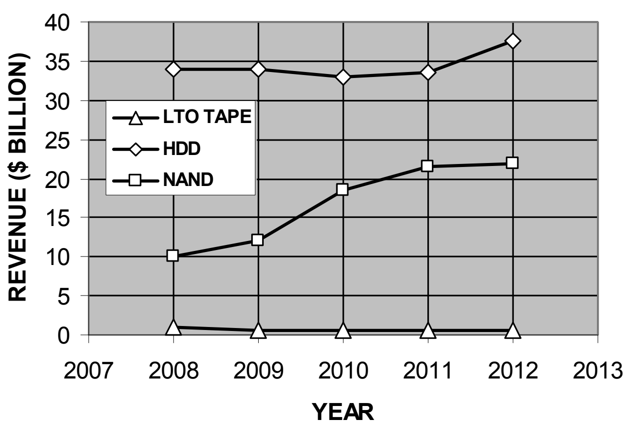

Figure 1. Five year history of revenue for LTO TAPE cartridges, HDD drives, and NAND flash memory chips. Total 2012 revenue ~ $60B

three years only one new areal density product, LTO5, has been introduced. Only in late 2012 was a 2.1 Gbit/in² LTO6 product introduced bringing areal density increases for TAPE closer to the 35% to 40% historical range. This paper will reference both the current 1.2 Gbit/in² and the 2.1 Gbit/in² areal densities for LTO TAPE.

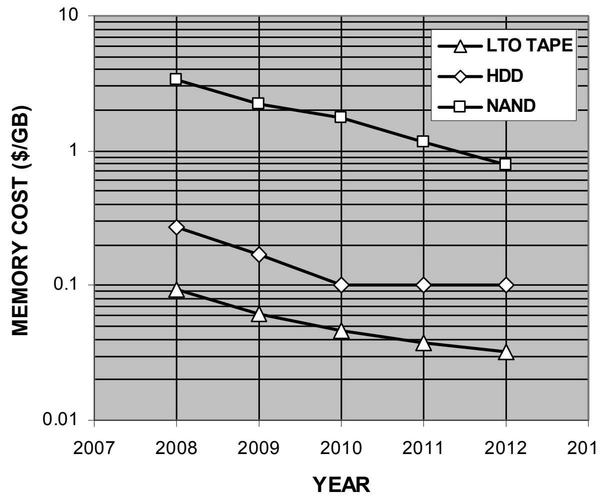

Figure 2. Five year history of memory cost ($/GB) for LTO TAPE, HDD, and NAND flash, showing stabilizing of HDD memory cost for last three years at $0.10/GB

Two trends shown from the data in Table I are 1) the slowing of revenue increases for companies manufacturing storage memory and 2) a marked slowing of the rate of decrease in HDD memory cost as measured in $/GB. These data are illustrated in Figure 1 and Figure 2.

Also, of note in Table I is the comparison of the differences between annual rate of growth of PB shipments for the three technologies and the annual growth rate of areal density increases over the 2008 to 2012 time span. Shortfall in areal density growth rate in maintaining PB shipment growth is made up by increasing manufacturing capacity. The specifics for PB shipment growth rates were: TAPE at 17%, NAND flash at 74%, HDD at 32%. The specifics for areal density growth rates were: TAPE at 8% (23% if YE2012 LTO6 technology is included), NAND flash at 29%, and HDD at 19%. The topic of this paper is to examine the difference between PB shipment increases and areal density increases and discuss how shortfalls in areal density increases are compensated for with increases in manufacturing capacity. Such an analysis requires an understanding of both the volumetric storage density and surface area density of TAPE, HDD, and NAND flash.

II. AREAL AND VOLUME METRICS FOR SCM

In addition to cost per bit, a key metric for storage is the true volumetric storage density, i.e. the number of bits in a physical volume. This volume measure is driven by three items: the areal metric of bits per unit area or areal density (see Table I), a volume metric related to the thickness of the media on which the bits are stored and how the media is configured into a component, and a volume metric related to the number of bits stored in the final component. The final component is a cartridge for TAPE, a hard disk drive for HDD, and a SSD for NAND flash. As will be shown, even though TAPE has areal densities that are a factor of 300 smaller than corresponding densities for HDD and NAND, all

Table II
Areal and Volume Metrics for TAPE, HDD, and NAND Flash
(Drive Environment)

	TAPE	HDD	NAND
Areal Density (Gbit/in²)	1.2-2.1	750	550
Media Spacing (component) mm	0.0054	1.00	0.25
Media Volumetric Density (TB/in³)	0.7-1.8	2.4	6.7
Component Volume (in³)	14.1	23.8	4.1
Typical Component Capacity (TB)	1.5-3.0	3.0-5.0	0.5
Component Volumetric Density (GB/in³)	106-212	126-210	121

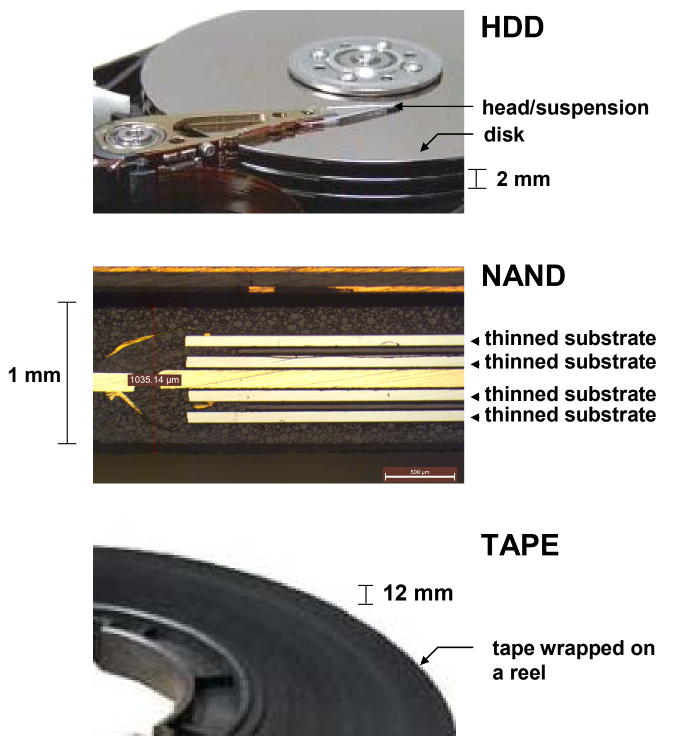

Fig. 3. Volumetric density for storage components based on media requirements within a drive component. Note the 4 thinned NAND substrates (~ 75 um) in the 1 mm thick NAND package cross-section [5]

three technologies compete effectively in the memory storage space since the volumetric densities for these three technologies are comparable at the final component level.

TAPE media is stacked in concentric layers on a reel with a pitch corresponding to the tape thickness of about 5.4 um. Disk media is arrayed in a stack of two sided platters with a 2 mm pitch corresponding to the platter thickness of 1 mm and to a 1mm space between platters for heads and suspensions. NAND media is the silicon substrate which, after processing is thinned from 800 um down to 75 um, with typically 4 thinned chips placed into a 1 mm package.

Table III
Volume Metrics for Specialized NAND Components

	Apple Gum Stick SSD Drive	Samsung Memory Module
Application	PC	Smart Phone
Capacity	512 GB	64 GB
Length	109 mm	15 mm
Width	24 mm	11 mm
Thickness	3.9 mm	1.2 mm
Volume	0.7 in³	0.012 in³
Component Storage Density	731 GB/in³	5333 GB/in³

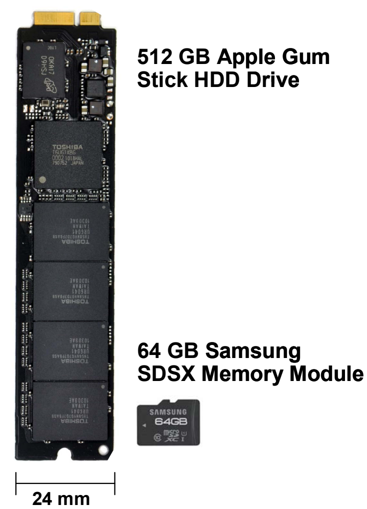

Figure 4. Variations in volume metrics for NAND devices used in Table III

From a component perspective, densities are correlated to an LTO cartridge volume, a 3.5" HDD enclosure, and an SSD disk conforming to a 2.5" HDD enclosure. Table II shows the volumetric densities for the three technologies in a drive environment. From this table the volumetric storage density for TAPE and HDD are almost comparable and the NAND media volumetric storage density is actually a factor of 2 to 3 greater than either TAPE or HDD storage densities. Of note, independent of areal density, TAPE is competitive with NAND and HDD from a volumetric storage density perspective. NAND has a competitive advantage when considering media volumetric densities implying significant advantages in consumer applications. Figure 3 illustrates the volumetric media densities described in Table II. It should be noted that in mobile storage applications which are not constrained by drive form factor standards, NAND flash has a considerable advantage in volume metrics over HDD and TAPE. As illustrated in Table III, Apple Corporation uses a 512 GB SSD hard drive with a "gum stick" form factor and a component volumetric storage density of 730 GB/in³ and Samsung Corporation uses a 64 GB memory card with an SDSX form factor and a component volumetric storage density of 5333 GB/in³. The later capacity is accomplished using 8 stacked and thinned (< 75 um) NAND chips in a 1.2 mm package. Figure 4 illustrates the dramatic range of bit storage density in packages described in Table III that can be realized by NAND devices. However, it is important to recognize that for SCM applications traditional volume measures usually concentrate on HDD from factors.

III. AREAL EFFICIENCY AND MANUFACTURING CAPACITY

A measure of manufacturing capacity requirements for various SCM memories is a calculation of the surface area of media that is produced annually for each of the technologies. The semiconductor industry refers to a measure of this manufacturing capacity as millions of square inches (MSI) produced. Ideally, a storage technology sustains PB shipments by areal density increases without increasing MSI, i.e. manufacturing infrastructure; the exception being when increasing market share provides financial incentives for more capacity investment. Calculating MSI depends on two parameters: the areal density product mix of the technology and the areal efficiency with which bits are placed onto the media. Typically, the areal efficiency of a technology is ~ 60% relative to the maximum areal density of the technology since on the media surface about 40% of the area is used for data management, data access, and pads (in the case of NAND devices). Table IV illustrates this result.

An estimate for calculating MSI for the SCM technologies is to use the data in Table I and Table IV and to assume that all technologies produce memory using the maximum areal density available. Using maximum areal density for determining MSI values is an underestimate, likely a factor of 2, but, with the exception of LTO TAPE, areal density product mixes are not publically available. For example, breakdowns of NAND production for 24 nm and 20 nm devices are not available and product mixes for HDD at the 1 TB per 3.5" platter vs. the more conservative 0.75 TB per 3.5" platter are not available. Nevertheless, relative comparisons are still valid.

2012 MSI values are as follows using area values in Table IV. For HDD drives, 380,000 PB are equivalent to 770,000,000 0.5 TB 90 mm diameter disk surfaces or 6,950 MSI. For TAPE, 19,500 PB are equivalent to 13,000,000 1.5 TB cartridges or 210,745 MSI. For NAND, the MSI calculation approach is different. Here MSI uses the IC standard 300 mm diameter Si wafer that accommodates approximately 522 8 GB chips at the 20 nm process node or 4.2TB of NAND flash per wafer. 28,000 PB for NAND are equivalent to 6,660,000 300 mm wafers or 730 MSI. Scaling the above data for the years 2008, 2009, 2010 with the PB values and areal density values of Table I yield the following MSI and areal density values shown in Table V and Table VI.

Table V and Table VI data can be interpreted with the aid of Figure 5, Figure 6, and Figure 7. Figure 5 plots PB shipments for memory technologies normalized to 2008 values. Figure 6 plots MSI production for memory technologies normalized to 2008 values. Figure 7 plots areal density increases normalized to 2008 values. In its simplest form PB shipments are the product of MSI (i.e. manufacturing of storage medium surface area) and AD or areal density (i.e. a measure of the number of bit cells configured per unit area). Observations are as follows: 1) anticipated consumer demand enabled substantial manufacturing investment (MSI) for both HDD and NAND. (the MSI decrease in 2011 for HDD is attributed to supply line issues in Asia related to natural disasters), 2) LTO TAPE percentage increase in its manufacturing capacity was 3x less than both HDD and NAND representing a lack of a consumer base market, 3) NAND PB shipments benefited from a substantial increase in areal density over the last 5 year period, averaging 36% per year vs HDDs average of 11% per year, and 4) contributions to NAND PB shipments come from both

Table IV
Density Efficiencies in Components

	HDD	**NAND**	**TAPE**
Media	2 sided disk	chip	tape
Dimension	90 mm disk 24 mm hub	12.5 mm x 9.5 mm	840 m length 12.5 mm high
Area (mm²)	11800	118	10,500,000
Areal Density	750 Gbit/in²	550 Gbit/in²	1.2 Gbit/in²
Capacity-max	1771 GB	13 GB	2520 GB
Capacity- actual	1000 GB	8 GB	1500 GB
Efficiency	56%	61%	60%

Table V
MSI, PD, and Areal Density (AD) Normalized to YE2008

	YE 2008	**YE 2009**	**YE 2010**	**YE 2011**	**YE 2012**
HDD					
MSI	4512	5176	7128	6127	6950
MSI/MSI(2008)	1.00	1.15	1.58	1.36	1.54
PB / PB(2008)	1.00	1.60	2.64	2.68	3.04
AD / AD(2008)	1.00	1.39	1.67	1.97	1.97
NAND					
MSI	215	278	455	485	730
MSI / MSI(2008)	1.00	1.29	2.11	2.25	3.39
PB / PB(2008)	1.00	1.81	3.49	6.20	9.33
AD / AD(2008)	1.00	1.40	1.65	2.75	2.75
TAPE					
MSI	149683	175296	165353	192372	210745
MSI / MSI(2008)	1.00	1.17	1.10	1.28	1.40
PB / PB(2008)	1.00	1.17	1.47	1.71	1.88
AD / AD(2008)	1.00	1.00	1.33	1.33	1.33

Table VI
Year to Year Percentage Increases in MSI, PB, and AD (Areal Density)

	YE 2008	YE 2009	YE 2010	YE 2011	YE 2012	Annual Average
HDD						
PB	----	60%	65%	2%	13%	32%
MSI	----	15%	38%	-14%	13%	11%
AD	----	39%	20%	18%	0%	19%
NAND						
PB	----	81%	93%	78%	51%	74%
MSI	----	29%	64%	7%	51%	36%
AD	----	40%	18%	67%	0%	29%
TAPE						
PB	----	17%	26%	16%	10%	17%
MSI	----	17%	-6%	16%	10%	9%
AD	----	0%	33%	0%	0%	8% (23%)[1]

1. Using YE2012 AD for LTO6 of 2.1 $Gbit/in^2$

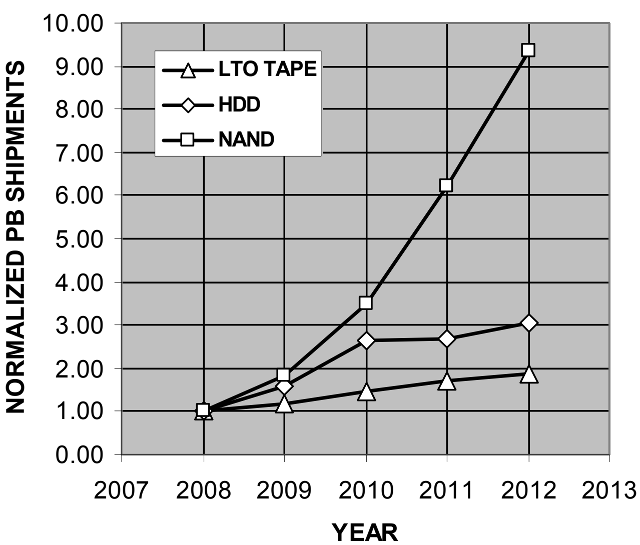

Figure 5. PB Shipments for LTO TAPE, HDD, and NAND flash normalized to 2008 values. Note the drop in HDD PB shipments in 2011 due to supply channel problems related to natural disasters in Thailand manufacturing capacity

substantial MSI investment and substantial areal density increases and dramatically outpace MSI investments in HDD.

Figure 7 shows stabilization in areal density increases over the last two years. This may reflect both the difficulty in technologies achieving higher areal densities [9] and the desire of the storage component industry to maximize manufacturing investment at each new technology node. Figure 6 shows the magnitude of the manufacturing commitment (MSI) in the NAND industry as compared to both HDD and TAPE.

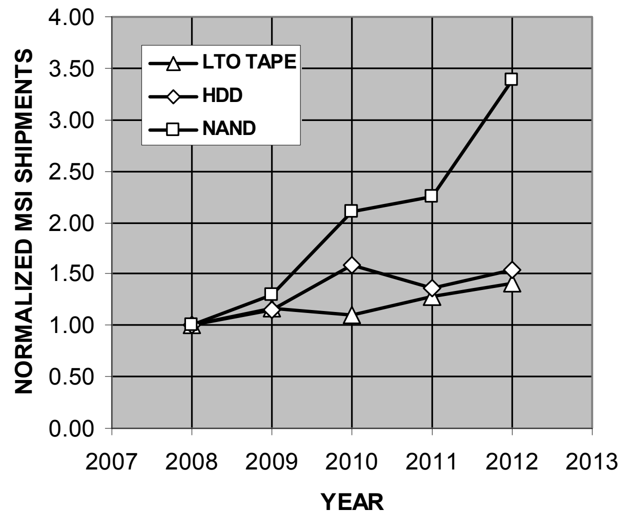

Figure 6. MSI manufacturing for LTO TAPE, HDD, and NAND flash normalized to 2008 values. Note the drop in MSI requirement for TAPE in 2010 due to product areal density increase

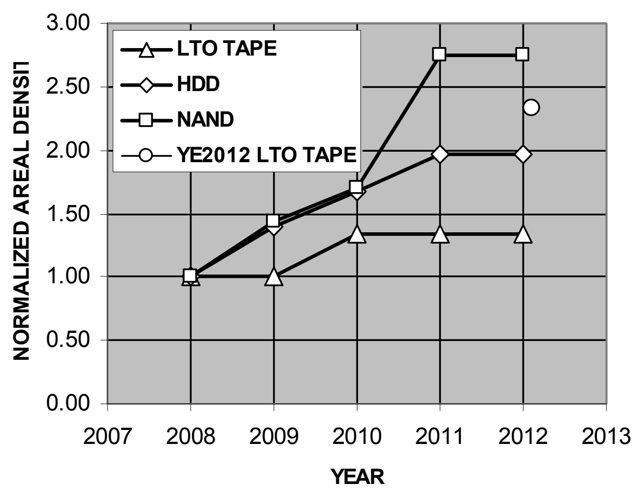

Figure 7. Areal density (AD) for LTO TAPE, HDD, and NAND flash normalized to 2008 values. Note the YE2012 areal density point for LTO TAPE that brings density increases for all three technologies closer to parity

However, note that the HDD industry produces 13X more PB than the NAND industry. Figure 5 shows the dramatic PB shipment growth for the NAND industry driven by MSI and areal density increases.

IV. MSI and Future Petabyte Shipments

The MSI concept can be applied to the various storage class memories to estimate costs for increased manufacturing when areal density does not meet the 40% annual increase rate. Examples follow.

For NAND, MSI calculations use as a base a \$3.5B IC facility [6] processing 1000 300 mm diameter wafers daily to produce 40 MSI annually of NAND. This calculation extends the work of Hetzler [7] to the present lithography node. Specifically, at the present 20 nm lithography node, as noted in Section III, each wafer contains 4.2 TB of storage so this facility produces 1533 PB of storage. Since NAND flash minimum feature is anticipated to decrease 10% annually as show by the ITRS roadmap data [8] overlaid with HDD requirements [9] in Figure 8, implying a 20% increase in annual areal density, the PB shipment shortfall could be met by increasing the number of NAND facilities. The NAND data above suggest that a 20% shortfall in NAND PB shipments (5600 PB) could be met with adding 4 IC facilities at a total coast of \$14B. Another implication of this MSI calculation is that for NAND to replace the entire HDD enterprise applications (50,000 PB) would require 33 IC facilities at a total capitalization of \$100B, an unlikely investment for the IC industry.

Table VII extends this capitalization argument further by estimating the facility requirements to replace the entire HDD PB output with NAND flash. The reality is that the capitalization cost of \$864B is not feasible and this is the primary reason that HDD will be a dominate storage medium for the foreseeable future. More critically, viewing the numbers in Table VII seems to show that replacement of all HDD enterprise applications is not likely. For HDD technology and capacity issues, the MSI concept, coupled with NAND processing numbers, can be used to estimate the cost of converting continuous HDD media to patterned media. This is a strategy contemplated by the HDD industry to move to smaller bit cell sizes. In essence, the strategy abandons continuous media, a low cost enabler for present HDD products, in order to pursue higher areal densities. One approach to estimate cost is to note that a NAND process requires about 25 mask steps and to assume the HDD patterning process is equivalent to one NAND mask step, i.e. lithography, deposition, patterning. So a \$3.5 billion NAND facility actually processes ~1,000MSI of single surfaces. This would imply the need for 7 such facilities to process the ~7,000 MSI of storage fabricated last year to deliver 380,000 PB. However, since deposition capability for HDD media exists, the estimate could be scaled by ~33% to 4 such facilities or \$14B in capitalization. Another approach to estimate pattern media disk cost is to note that the average cost of a 300 mm processed Si wafer is about \$1500 or \$60 per mask layer or \$0.53/in². This translates to patterned media costs of ~ \$5 for a 2.5” diameter platter and ~ \$10 for 3.5” diameter platter. These costs should be contrasted to present day 3.5” diameter disk costs in the \$3 range. To estimate a 20% shortfall in HDD PB shipments should HDD densities increase only by 20% in the next year, the MSI investment calculation is less straightforward. One must assume a head cost and disk cost, numbers not readily available, associated with producing an additional 130,000,000 disk surfaces and 130,000,000 heads based on YE2011 MSI estimates. If one assumed costs of \$1.50 for head and \$1.50 for a disk surface, the 20% areal density shortfall would imply new component costs of \$0.5B.

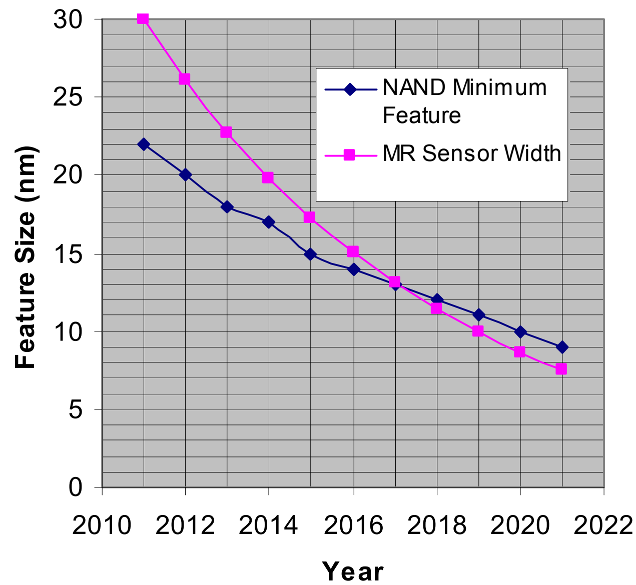

Figure 8. Minimum feature size projections for HDD and NAND technologies. NAND technology data from ITRS 2012 final report [8].

Table VII: NAND Capitalization Scenarios for HDD Replacement[1]

	NAND Reference YE2012	NAND Replaces All HDD	NAND Replaces HDD Enterprise
PB	28000	380000	50,000
MSI	730	9907	1304
MEGA FABS	18	247	33
CAPITAL	\$63B	\$864B	\$115B

1) Calculation based on \$3.5B capitalization for a Mega FAB producing 1000 300 mm NAND wafers daily

An analysis of TAPE MSI needs, or specifically in this paper LTO TAPE, requires some special discussion. Unlike HDD and NAND, TAPE supports several areal density products over a 2X range at any one time. An LTO Product Generation may span 8 years as shown in Figure 9.

The LTO environment at YE2012 supported three areal densities: 1.2 Gbit/in², 0.9 Gbit/in², and 0.75 Gb/in² corresponding to tape cartridge capacities of 1.5T, 0.8TB, and 0.4TB which were introduced in 2009, 2006, and 2004. Specifically, in 2012, LTO5 products accounted for 9200 PB, LTO4 products accounted for 7950 PB, and LTO3 products accounted for 2020 PB [2]. The LTO consortium introduced the LTO6 product generation in late 2012 with tape capacities in excess of 2.5 TB based on areal densities in the 2.1 Gbit/in² range or a 75% density increase over LTO5 products. Assuming that the LTO areal density roadmap maintains these types of areal density maintaining historical PB shipment increases of 20% to 30% per year will require minimal MSI

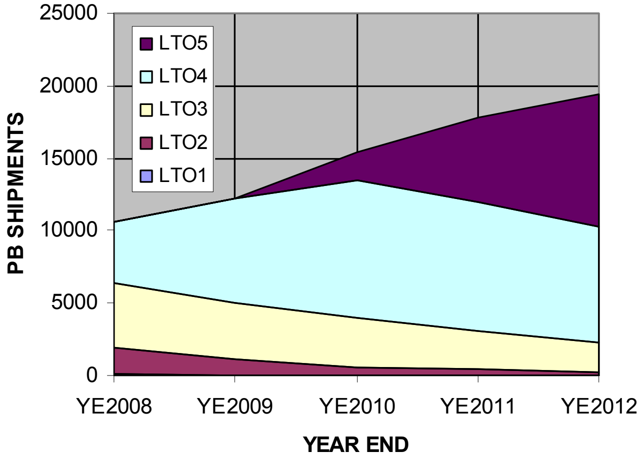

Figure 9. PB shipment history for LTO products showing >5 year product lifetimes and three simultaneous products with significant PB volumes. Note that the LTO5 introduction in 2009 required 3 years of production to obtain the highest market share in the LTO family

increases since manufacturing capacity is simply shifting from the older generation density products to higher density products. This observation likely accounts for the steady reduction in cost per bit for TAPE. Unlike HDD and NAND, the LTO TAPE environment is not consumer based. Demand is driven by large data applications (archival and enterprise).

V. PETABYTE MEMORY VOLUMES

The data in Table I provide an opportunity to evaluate the amount of storage used in the data community. Specifically by integrating the total amount of storage produced over the past 5 years (the bulk of which comes from HDD products), one can estimate how much storage is presently available for storing created data. There appears to be a consensus that data creation is increasing at 50% per year [1] and that present data creation is in excess of 2,000,000 PB or 2 ZB (Zeta Byte). Yet, from Table I, 420,000 PB were manufactured in 2012. This is illustrated in Figure 10 by taking the data of Chernery [1] and overlaying these data with PB shipments for the last 5 years and, in particular, accumulating for each year all PB shipments manufactured since 2008. These data for 2012 are as follows: 2012 information created -- 2.7 ZB, 2012 available storage memory (from 2008) -- 1.5 ZB, 2012 storage memory manufactured -- 0.43 ZB, and a shortfall between data created and available manufactured memory of 1.2 ZB. One reality for these data is that one may question the validity of information creation at 2.7 ZB for 2012. It is difficult to account for 1.2 ZB of storage media to make up the storage shortfall. A second reality, and more critical, is that today annual increases in manufactured storage memory are not at 50% rates but rather 30% rates driven by the HDD industry. Also, the HDD industry has slowed its PB shipment growth

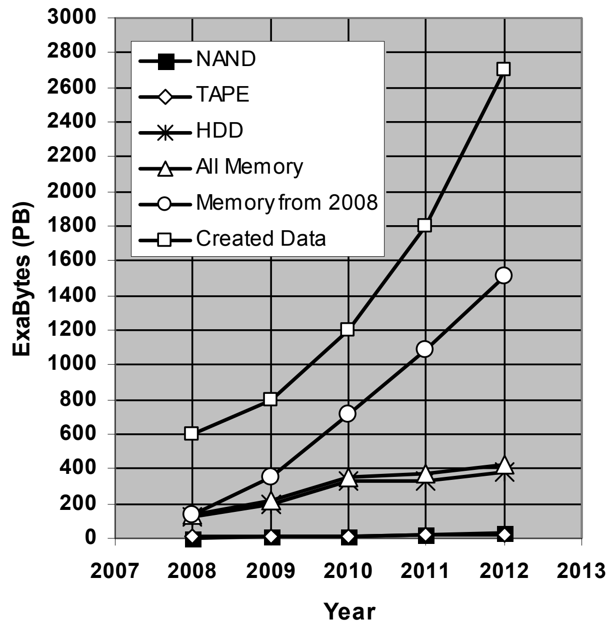

Figure 10. Data creation [1] and total amount of storage memory manufactured expressed in EB for the period 2008 through 2012. The "Memory from 2008" curve represents all memory manufactured with a starting point of 2008

Table VIII
Year to Year Percentage Increases in HDD PB, Total PB Produced, and Cumulative PB Produced since 2008, and Annual Information Created

	HDD PB Manufactured Annually	Total PB Manufactured Annually	Cumulative PB Produced since 2008¹	Annual PB of Information Created
2008	----	----	----	----
2009	60%	56%	156%	33%
2010	65%	64%	100%	50%
2011	1.5%	42%	52%	50%
2012	13%	15%²	39%	50%²
5 Year Average	32%	32%	81%	45%

1. The 81% average rate of increase for Cumulative PB Produced since 2008 is a product of starting the accumulation in 2008 with low PB volumes.
2. The 2012 data are more relevant and show annual increase rates of Manufactured PB falling significantly below annual rates of Information Creation.

rate in 2011 and 2012 while stabilizing cost per GB. The implication of these observations is that the future cost and volume environment for storage media appears to be changing. These rates of increase are illustrated in Table VIII.

VI. SUMMARY

This paper has presented a 5 year history of PB shipments and areal density increases for LTO TAPE, HDD, and NAND Flash SCM technologies. From these data, a manufacturing measure, MSI, has been developed to evaluate manufacturing capability for these three storage technologies. HDD and NAND Flash will require increased manufacturing or MSI investment to sustain growth in PB shipments since areal density increases are slowing. TAPE, on the other hand, is available to sustain areal density growth and will require minimum MSI investment. MSI calculations allow one to quantify the MSI investment and point to the advantage, not unanticipated, of continuing areal density increases to offset manufacturing investment; an advantage that TAPE has relative to HDD and NAND Flash. Finally, manufactured PBs of storage are growing at 30% per year while information creation (i.e. demand) is increasing at 50% per year leading to changes in the cost and volume environment for manufactured storage.

ACKNOWLEDGMENT

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