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

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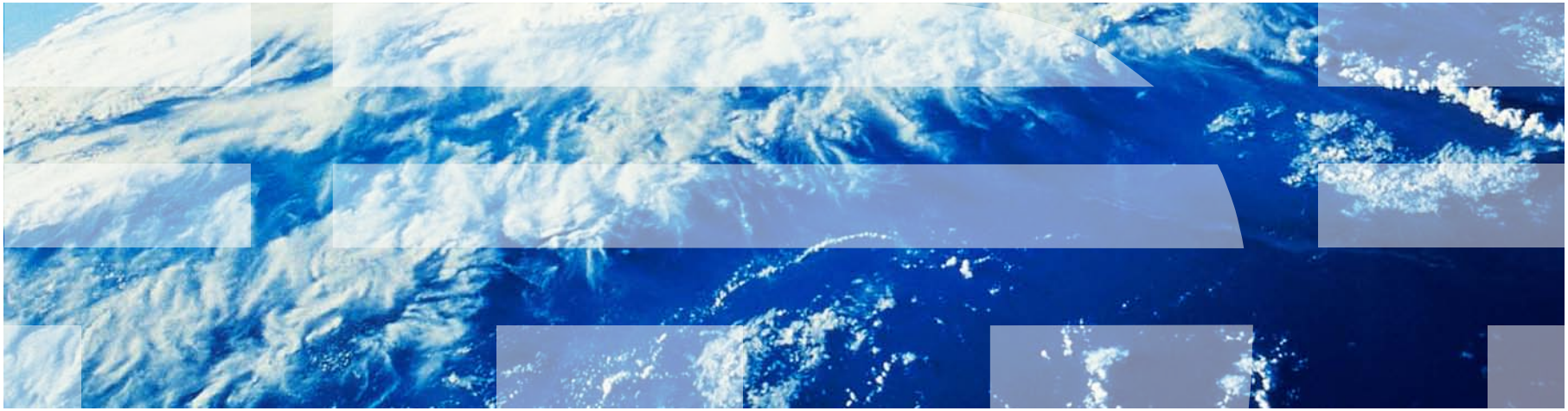
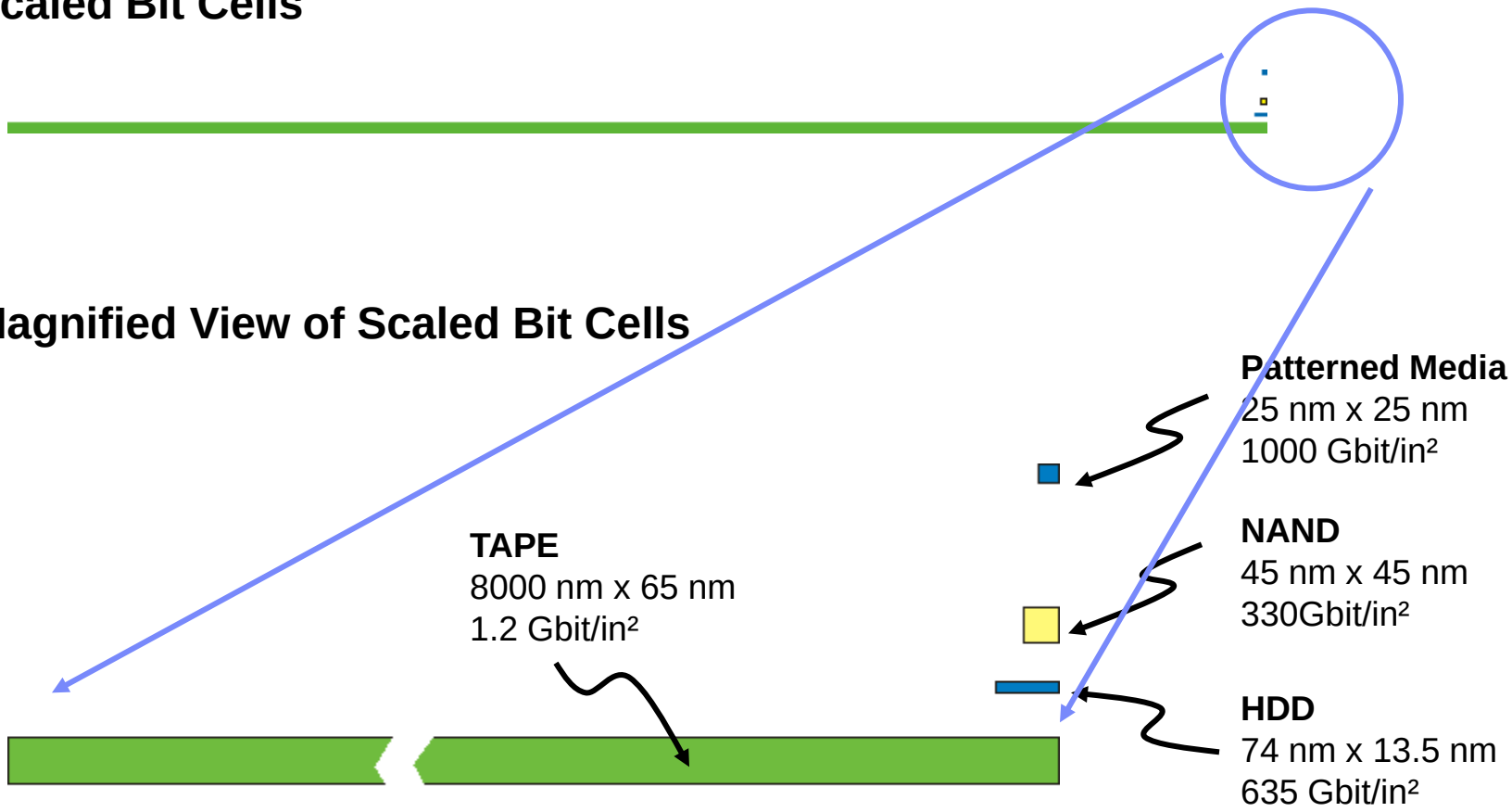


Storage Bit Cells (last years topic)

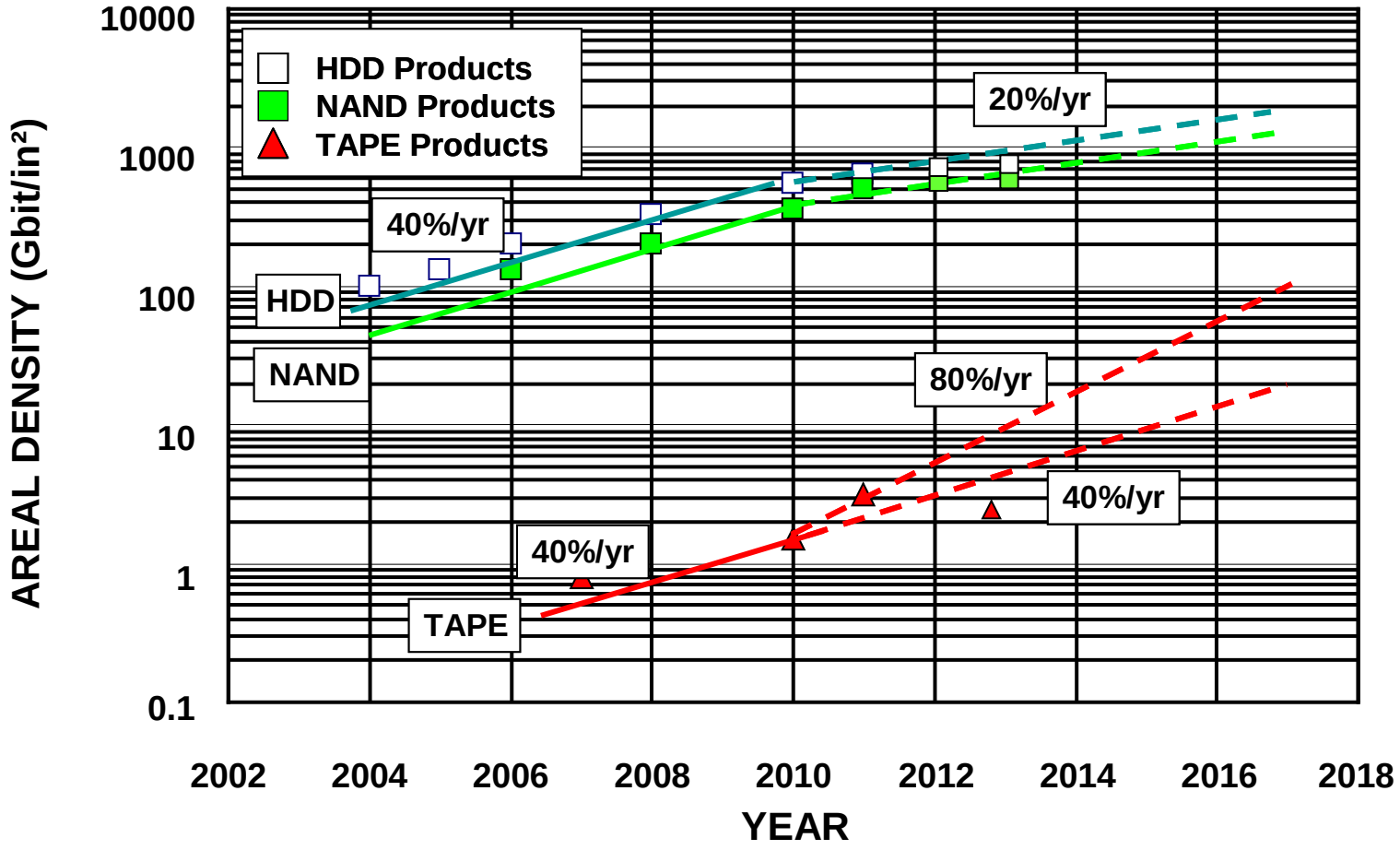
- **Scaled Bit Cells**

- **Magnified View of Scaled Bit Cells**



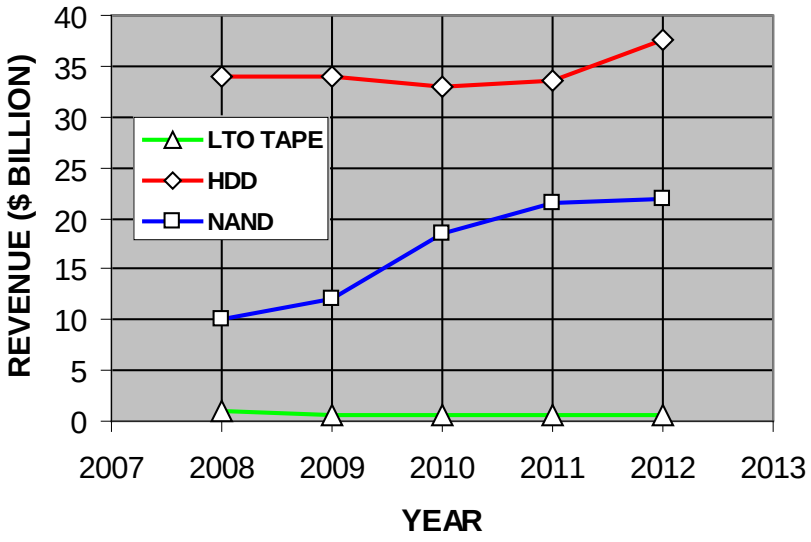
Some Background

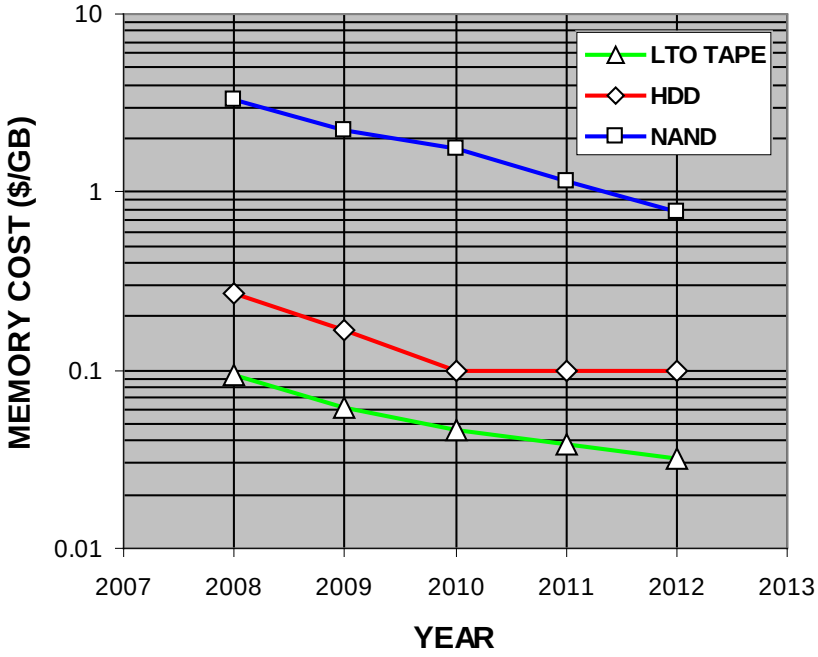
- As petabyte shipment demands for memory increase at a greater rate than areal density improvements (the technology metric that allows one to manufacture more bits per unit area), increases in manufacturing investment (the ability to produce millions of square inches, i.e. area or MSI, of memory) will occur. MSI is expensive!



Revenue and Cost Per Bit

- Revenue = Petabytes Shipped (PB) x Cost per Byte ($/GB)
- PB Shipped = Areal Density (AD) x Millions of Square Inches (MSI) of Manufactured Memory
- Revenue dynamics for storage components assume ever increasing PB shipments coming from ever increasing areal densities with moderate investment in manufacturing capacity (MSI)
  - Cost / Byte or $/GB decreases are slowing as areal density increases slow
  - Revenues for manufactures are not showing significant increases
  - Increasing MSI is expensive





Millions of Square Inches (MSI)

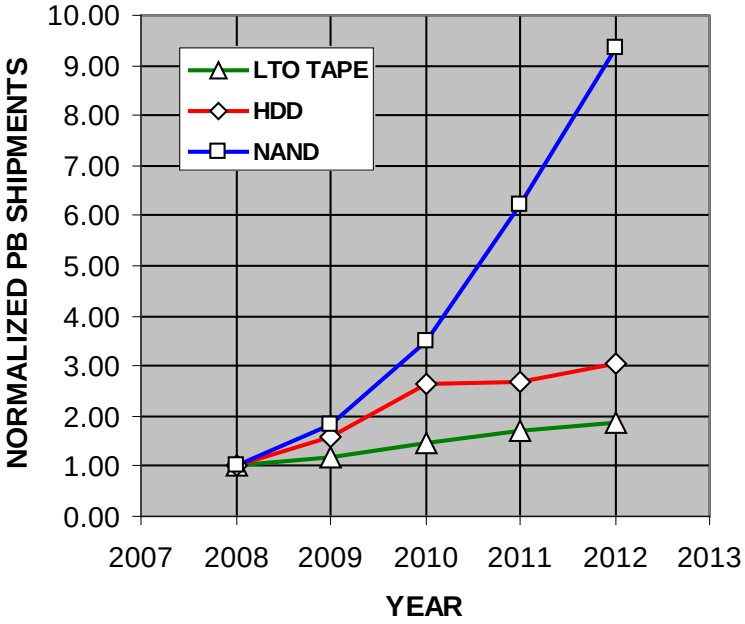
Areal Density (AD) x Millions of Square Inches (MSI) = Petabytes (PB)

- Example
  - If PB demand is perceived to increase at 60% per year and if AD increases at 40% per year then MSI or manufacturing capacity must increase at 20% per year.
  - MSI requires capital expenditures which in the near term raise the cost per bit
  - Technology improvements in TAPE, HDD, and NAND must be sensitive to manufacturing investments

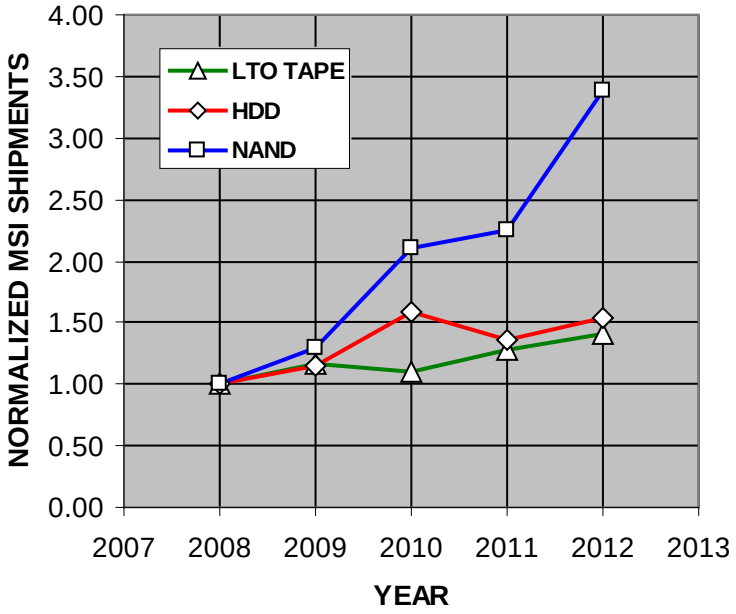
- Agenda
  - Five year history of PB, AD, and Revenue for TAPE, HDD, and NAND
  - Areal and Volume Metrics discussion
  - Description of MSI
  - MSI Applications

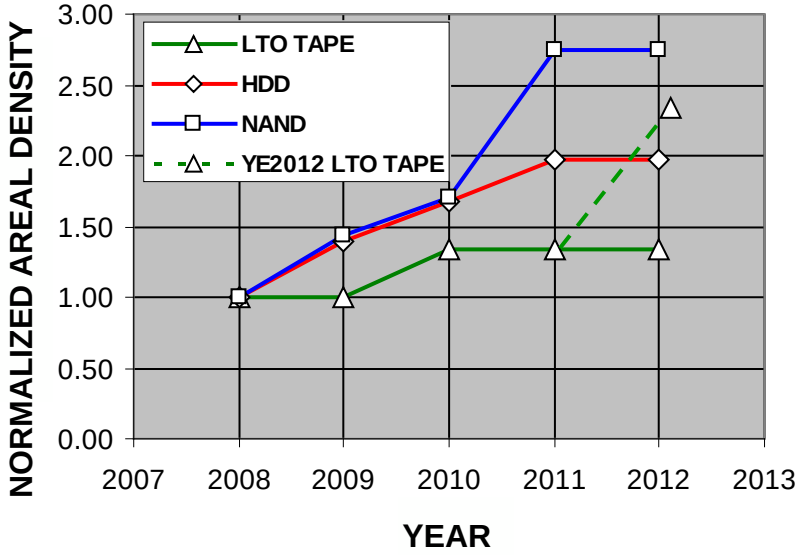
- Key Points
  - Use MSI to evaluate new technology improvements for HDD
  - Use MSI to compare replacement costs for NAND over HDD
  - PB demand at 60% per year increases may be overstated in an environment of < 30% areal density increases
  - Provide the MSST community with scale of PB volumes for storage

PB = MSI x AD



- 9 fold increase in NAND PB shipments
- 3.5 fold increase in NAND MSI
- 2.75 fold increase in NAND AD
- No change in AD last two years for all technologies
- Marginal increase in MSI (manufacturing capacity) for HDD and TAPE for last two years





5 Year History – PB, AD, Revenue

	YE 2008	YE2009	YE2010	YE2011	YE2012[1]
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
$/GB Shipped	3.33	2.23	1.77	1.16	0.78
LTO TAPE					
Units (Cart. millions)	20	24	25	25	22.7
PB Shipped (PB)	10400	12165	15300	17800	19500
Areal Density (Gb/in²)	0.9	0.9	1.2	1.2	1.2[2]
Revenue ($ billions)	1.0	0.7	0.7	0.7	0.62
$/GB Shipped	0.093	0.061	0.046	0.038	0.032

-Consumer Base
-Industry Restructure
-50000 PB Enterprise in 2011

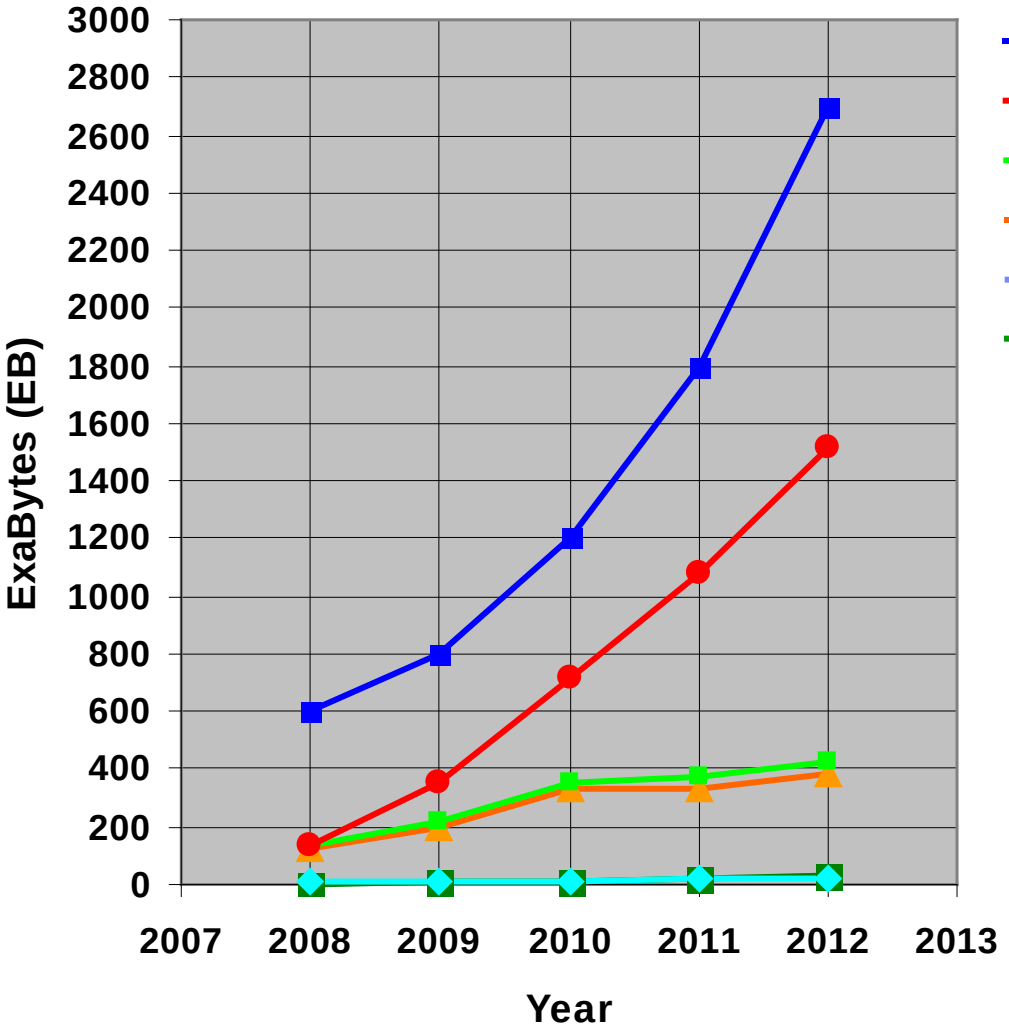
-Consumer Base
-Capital Investment
-20 nm Lithography
-1000 PB Enterprise in 2011

-No Consumer Base
-Rigid 2 Year Product Introduction Cycle
-17800 PB Enterprise/ Archive in 2011

1. 2012 data extrapolated from 3Q2012 values and minimal 4Q2012 data
2. LTO6 was introduced in late 4Q2012 and areal density value not included in Table, i.e. ~ 2.2 Gbit/in²

EB Environment (2008 through 2012)

- EB gap between storage produced and data generated?



1. M. Chernery, AIS 2011 Conference, Slide 11, Nov. 2011, www.lsi/AIS2011/Documents/LSIKeynoteMikeChernery.pdf

Areal and Volume Metrics

- Areal Density – Number of bits per unit area, usually defined as the maximum number of bits per unit area. Areal Density excludes unused space for tape edges, clocking and drive circuits in a NAND chip, and servo information and banding effects in an HDD.

- Media Volume Density – Number of bits per unit volume on a substrate (within a component) that supports the memory cell. (substrate stacking within a final component)
  - 6 um thick tape
  - 75 um thinned silicon substrate (starting thickness in a FAB is 800 um) in a 1 mm package
  - An array of 2 surface disks on a 2 mm pitch

- Component Volume Density – Number of bits per unit volume in a final memory component

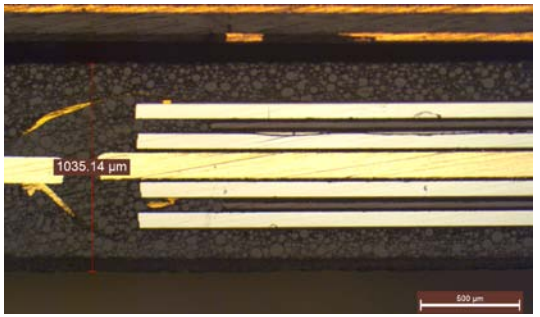
Technology	Form Factor	Length	Width	Thickness	Volume
TAPE	LTO Cartridge	102 mm	105 mm	25.5 mm	14.1 in^3
HDD	3.5” Drive	147 mm	101 mm	26.1 mm	23.8 in^3
SSD	2.5” Drive	100 mm	69 mm	9.5 mm	4.1 in^3
SSD	Apple “Gum Stick”	109 mm	24 mm	3.9 mm	0.7 in^3

Volumetrics (Today) for HDD, NAND, TAPE

HDD (3 TB 3.5” Drive)
-- Areal Density 730 Gbit/in²
-- Media Density 2.4 Tb/in³
-- Component Density 126 GB/in³

NAND (0.5 TB 2.5” Form Factor Drive)
-- Areal Density 550 Gbit/in²
-- Media Density 6.7 Tb/in³
-- Component Density 121 GB/in³

NAND (0.5 TB Gum Stick Form Factor Drive)
-- Areal Density 550 Gbit/in²
-- Media Density 6.7 Tb/in³
-- Component Density 714 GB/in³



TAPE (1.5 TB LTO5 Cartridge)
-- Areal Density 1.2 Gbit/in²
-- Media Density 0.7Tb/in³
-- Component Density 106 GB/in³

Volumetric NAND Advantage

- NAND is not confined to the traditional HDD drive from factor. NAND chips can be thinned (i.e to 75 um) and stacked into packages

	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 in^3	0.012 in^3
Component Storage Density	731 GB/in^3	5333 GB/in^3

MSI (Millions of Square Inches) Concept

- TAPE, HDD, and SSD are surface area intensive technologies.
- The IC industry uses the MSI or Millions of Square Inches metric to evaluate manufacturing requirements for NAND and DRAM production
- MSI can be calculated by using the areal density product mix and the areal efficiency for a particular technology. Areal efficiency takes into account the overhead surface area used for data housekeeping, data access, and mechanical reliability
- Areal density product mixes are difficult to obtain so MSI can be estimated using maximum areal density values so that relative technology comparisons are possible

Areal Efficiency

	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%**

MSI Results

	YE 2008	YE 2009	YE 2010	YE 2011[1]	YE 2012
HDD[1]					
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[2]

- 4000 MSI = 1 mile²
- TAPE MSI calculated from number of cartridges shipped using 840 m tape length and 12.5 mm tape width == ***Very Accurate***
- NAND MSI calculated using reported areal efficiency for 20 nm 8 GB chip with 450 chips per 12” wafer == ***Less Accurate*** since all NAND devices are not at the 20 nm node
- HDD MSI calculated using the maximum areal density and areal efficiency for 3.5” disks == ***Least Accurate*** since percentage of HDD products using the highest areal density is not publically available
- 6230 MSI = Washington DC Mall
- 500 MSI = 62 Football Fields
- 199288 MSI = Washington DC

1. HDD aberration in YE2011 due to supply line issues

2. LTO 6 introduced YE2012 with areal density of 2.1 Gbit/in² would change 2012 areal density ratio to 2.30

MSI Results (Year to Year Perspective for 4 Years)

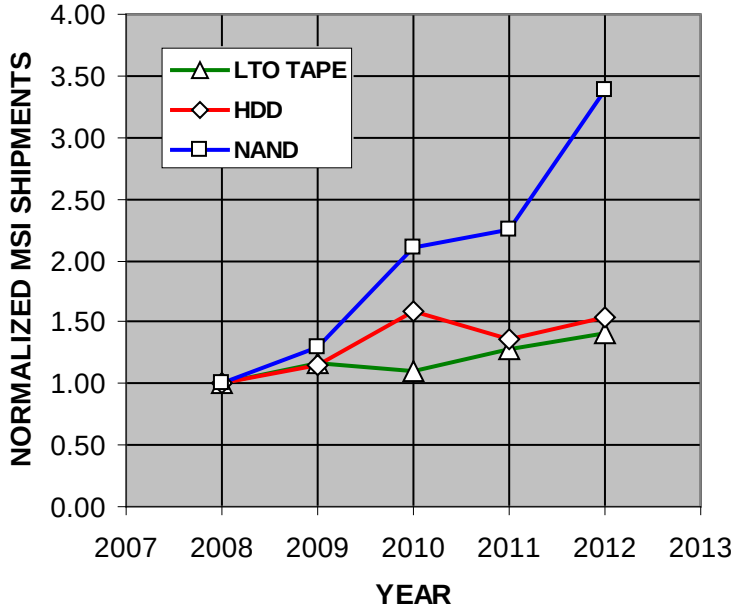
	YE 2008	YE 2009	YE 2010	YE 2011	YE 2012	Annual Average
HDD						
PB	----	60%	65%	2%	13%	32%
MSI	----	15%	38%	-14%[1]	13%	11%
AD	----	39%	20%	18%	0%	19%
NAND						
PB	----	81%	93%	78%	51%	74%
MSI	----	29%	64%	7%	51%	36%
AD	----	40%	18%	67%	0%	29%
TAPE						
PB	----	17%	26%	16%	10%	17%
MSI	----	17%	-6%	16%	10%	9%
AD	----	0%	33%	0%	0% (75%[2])	8% (23%[2])

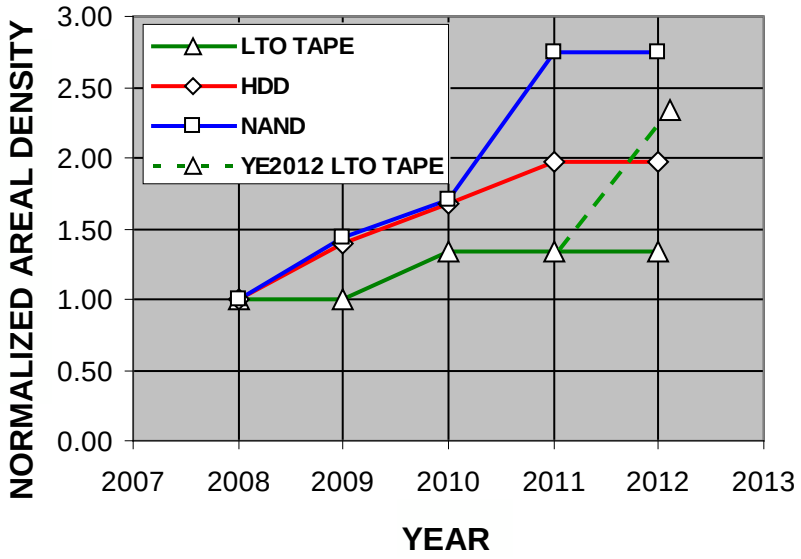
- NAND had both phenomenal MSI investment and areal density growth
- LTO TAPE with product introductions dictated by consortium requirements had small investments in MSI
- HDD had supply line issues in 2011 which distorts MSI. However, YE2010 data show large capital investment in MSI to accommodate lower areal density increase rates

1. HDD YE2011 aberration due to supply line issues

2. TAPE AD for YE2011 data using LTO 6 values

MSI Results (Year to Year Perspective for 4 Years)





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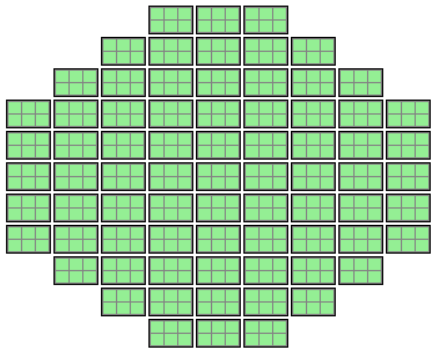
MSI Applications

- Estimate manufacturing requirements (cost) of NAND replacing HDD
- Estimate HDD manufacturing costs for patterned media
- A true example of MSI for TAPE
- The Metrics
  - A 300 mm NAND wafer contains 528 8GB chips or 4.2TB or storage
  - Raw wafer processing of the NAND wafer is ~$1500
  - The NAND chip is formed using 25 mask layers or planar processing steps
  - 1 completed NAND wafer is equivalent to 1.13×10^{-4} MSI of storage area
  - 1 completed NAND wafer is equivalent to 2.83×10^{-3} MSI of processing area



MSI Applications – NAND Replacing HDD

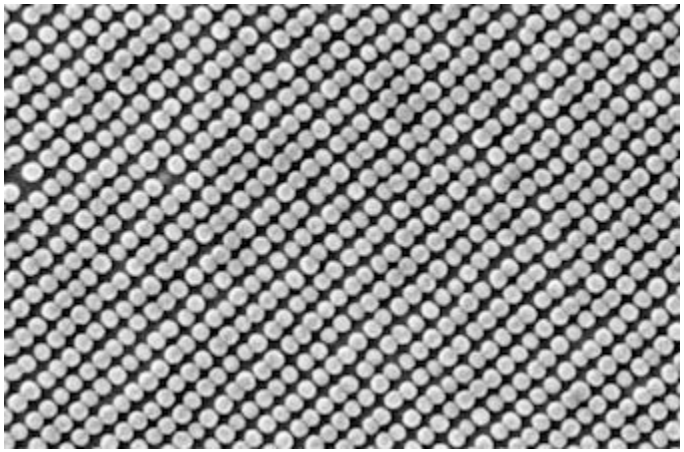
- Typical NAND FAB Numbers
  - $3.5 B MEGA FAB produces 1000 wafers per day
  - $9.0 B GIGA FAB produces 2600 wafers per day
  - 12” NAND wafer contains 522 8 GB chips (20 nm node) or 4.2 TB
  - $3.5B MEGA FAB produces 1533 PB annually or 41 MSI of memory annually

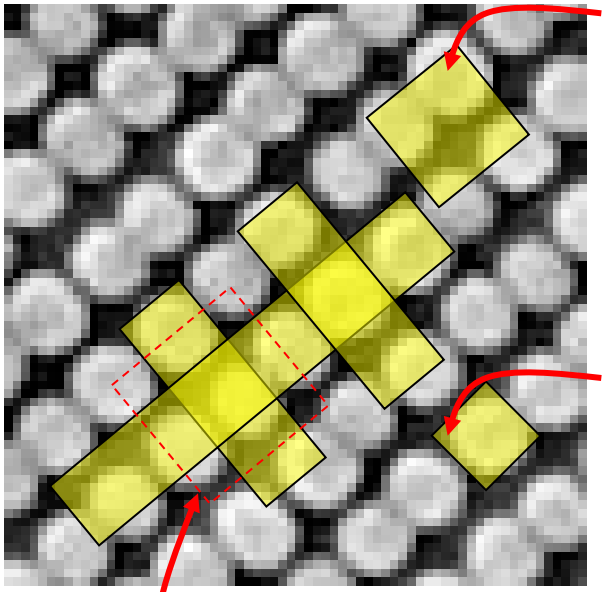
	NAND Reference (YE2012)	**NAND Replaces All HDD**	**NAND Replaces HDD Enterprise**
PB	28000	380000	50000
MSI	730	9907	1304
MEGA FABs	18	247	33
CAPITAL	$63 B	$864 B	$100 B

- Comment – HDD annual revenue is **$33B**

Pattern Media for HDD

- A major paradigm shift for HDD ➔ using isolated islands of media rather than continuous media to store magnetics bits on a disk surface.
- HDD is emulating NAND.
- An HGST (March 2013) example of 1.2 TDots /in² on a 22 nm pitch





MSI Applications – Pattern Media Disc Cost

- NAND 12” Processing Numbers for MEGA FAB at 41 MSI per year
  - NAND wafer area 113 in^2
  - NAND wafer masks 25
  - NAND wafer cost (ITRS) $1500
  - NAND wafer cost / in^2 $13.26
  - NAND wafer cost / in^2 / mask $0.53

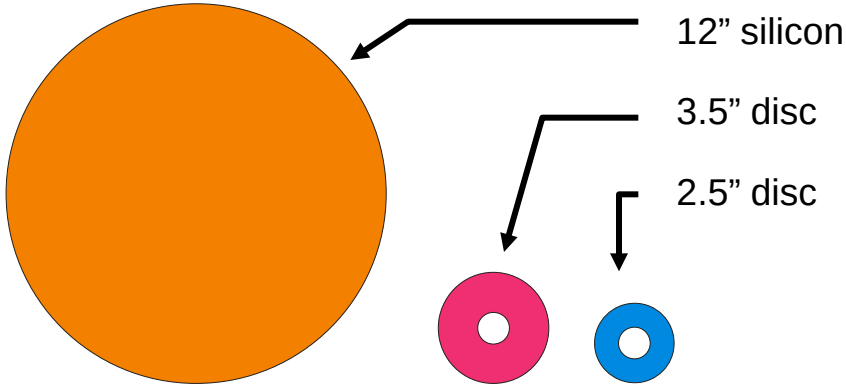
- Assumptions
  - A pattern media process is equivalent to one processing mask step in a NAND process, i.e. deposition, lithography, patterning.

- Disk Cost Results – An Upper Limit
  - 2.5” area for 2 surfaces is 9.8 in^2 implying $5.20 per 2.5” disk
  - 3.5” area for 2 surfaces is 19.2 in^2 implying $10.20 per 3.5” disk
  - ITRS reports that NAND mask numbers are increasing (35). If the wafer cost stays constant, the cost/in^2/mask assumption reduces. However the bulk of these masks are “low” degree of difficulty or “large” line width steps

- A Remark
  - NAND processing tolerates no defects as contrasted to the pattern media assertion that 1 in 10^4 dots may have a defect. The large defect density, at least at 1 Tdot/in^2, reduces disc processing cost relative to NAND processing costs
  - Patterned media defect density $1.6 \times 10^5/mm^2$
  - DRAM IC defect density (2012) $4.6 \times 10^{-5}/mm^2$

MSI Applications – Pattern Media Processing -- FABS

- Typical NAND 12” NAND MEGA FAB
  - Capitalization $3.5B
  - Wafer starts / day 1000
  - Device masks 25
  - MSI per year (device area) 41
  - MSI per year (process area) 1025

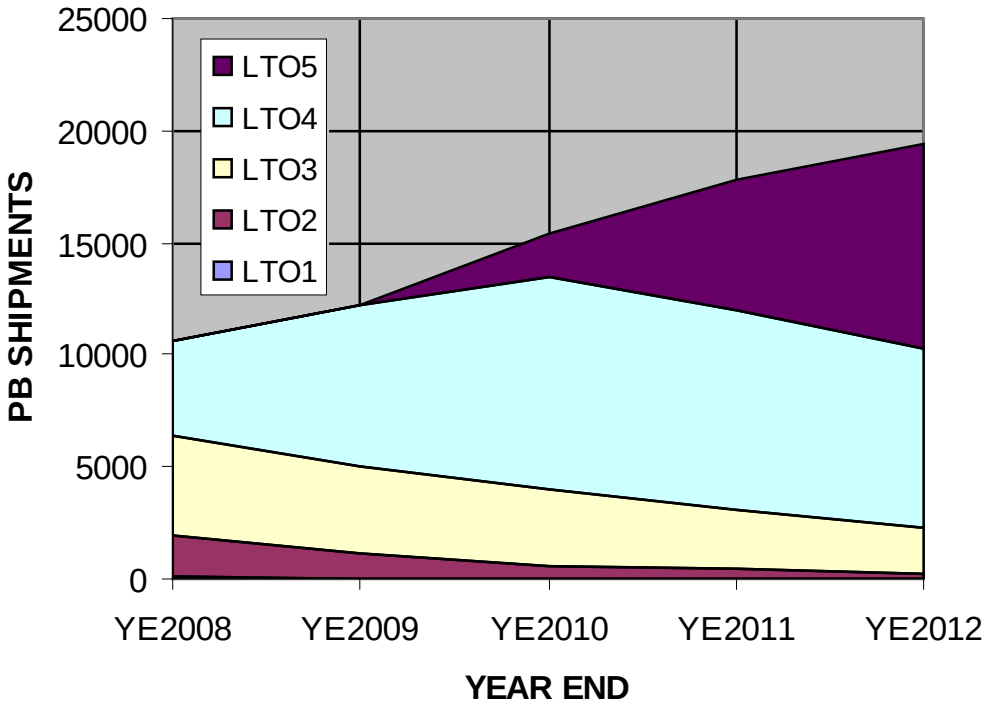


- MSI Implication at 1 Tb/in²
  - 3.5” disk surface capacity 0.65 TB
  - 3.5” surfaces for 330,000 PB 508,000,000
  - MSI of patterned surfaces 4873
  - MEGA FABS for equivalent MSI 5
  - MEGA FABS capitalization $17.5 B

- Notes and Comments
  - Existing deposition capabilities reduces capitalization by 33%
  - Product introduction at 1.5 TB/in² in 3 years reduces capitalization by 33%
  - Increasing PB shipments by 20% for each of these 3 years raises capitalization by 72%
  - NET ➔ $17.5 B x 0.67 x 0.67 x 1.72 = 0.77 x $17.5 B = $13 B

A More Accurate Estimate on MSI using TAPE as an example

- MSI calculations make the assumption that all PBs are manufactured using the maximum areal density since public access to areal density mixes are not readily available
- This strategy underestimates MSI and this underestimate is most severe with TAPE since TAPE is unique among storage memory technologies, i.e. 3 areal density products supported by one drive
  - Read/Write on GEN N tape
  - Read/Write on GEN N-1 tape
  - Read on GEN N-2 tape
- The Santa Clara Valley Consulting Group tracks all generations of LTO tape cartridge sales , and hence PB shipments, so accurate MSI calculations can be obtained



GENERATION	YE 2008	YE 2009	YE 2010	YE 2011	YE 2012
LT01 PB	108	29	25	25	23
LT02 PB	1790	1071	596	425	262
LT03 PB	4520	3876	3372	2676	2020
LT04 PB	4247	7189	9520	8830	7950
LT05 PB	---	---	1860	5858	9198
TOTAL PB	10665	12165	15373	17814	19453

A More Accurate Thought on TAPE MSI (continued)

- True LTO TAPE MSI is actually 1.8X the value computed by using maximum areal density

MSI DATA

GENERATION	YE2008	YE2009	YE2010	YE2011	YE2012
LT01	17577	4720	4069	4069	3678
LT02	145661	87153	48500	34584	21320
LT03	183908	157705	137198	108880	82189
LT04	86400	146251	193673	179635	161733
LT05	---	---	20181	63559	99798
TOTAL MSI	433560	395828	403620	390727	368719
MSI / MSI (2008)	1.00	**0.91**	**0.93**	**0.91**	**0.85**
TOTAL MSI	149683	175296	165353	192372	210745
MSI / MSI (2008)	1.00	1.17	1.10	1.28	1.40

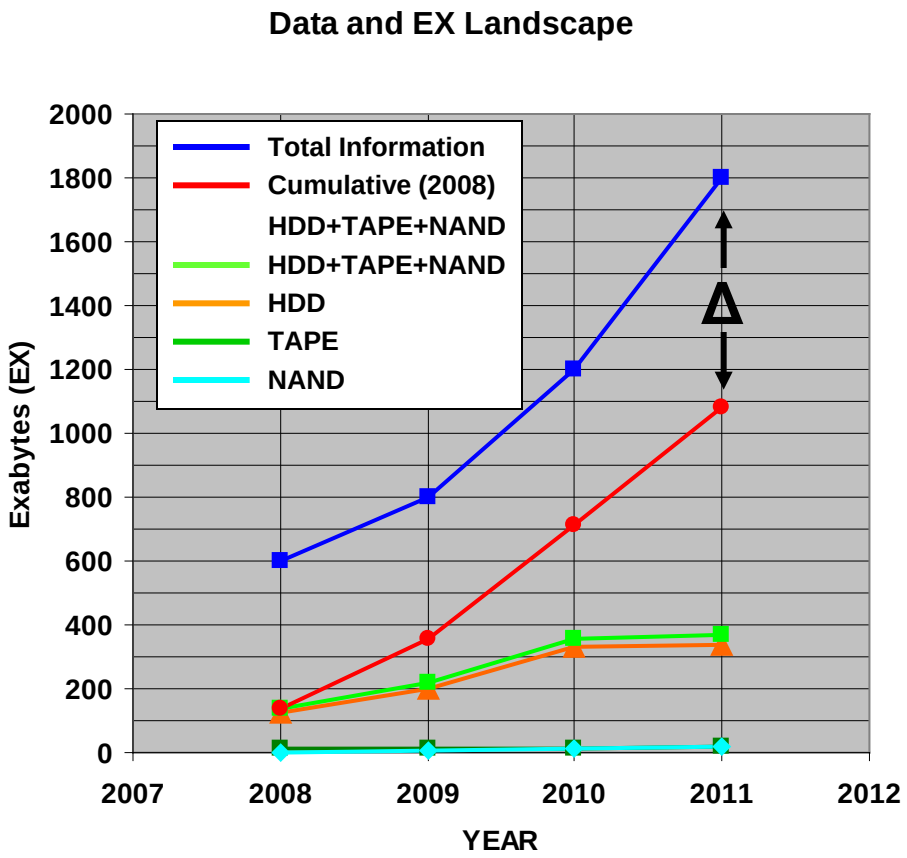
} **Data with true product mix**

} **Data with maximum areal density**

- For NAND the issue is converting from 24 nm to 20 nm design rules and converting from 1 bit per cell (2 levels) to 2 bits per cell (4 levels) and possibly, for consumer applications, to 3 bits per cell (8 levels).
- For HDD the issue is areal density mix and platter size mix

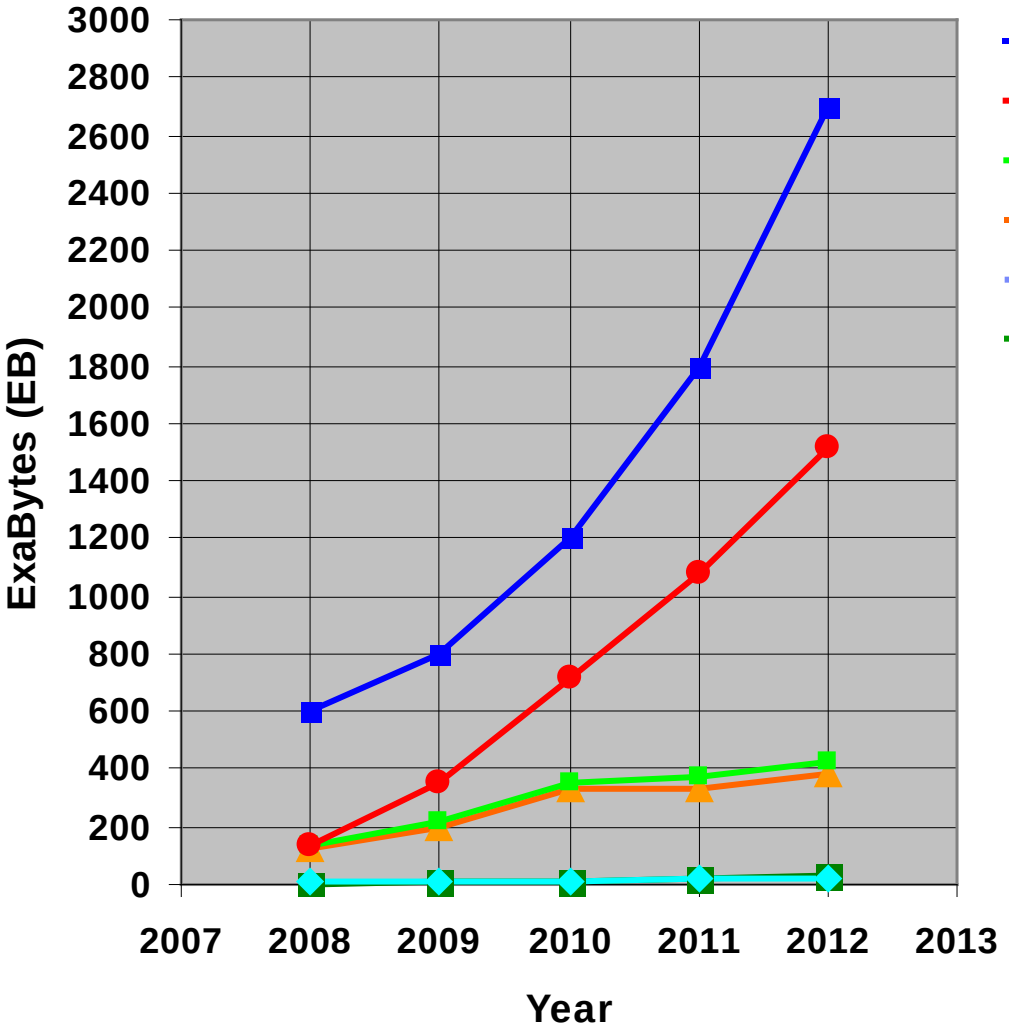
SUMMARY

- MSI is a standard IC measurement which gauges manufacturing requirements.
- MSI methodology has application not only to NAND but also to TAPE and HDD technologies
- Cost to manufacture NAND PBs volumes comparable to HDD PBs is prohibitive ($750T)
- PB shipments for NAND and HDD have historically relied on both MSI and AD increases
- Strategy of using maximum AD underestimates the MSI calculation
- PB shipments for TAPE are sustained by AD increases with lessened dependence on MSI
- MSI becomes more relevant to HDD when pattern media strategies are considered (HDD begins to emulate NAND)
- Where are all the PBs or MSIs or Exabytes?
- What can you do with this data



EB Environment (2008 through 2012)

- EB gap between storage produced and data generated? – Forecast data growth



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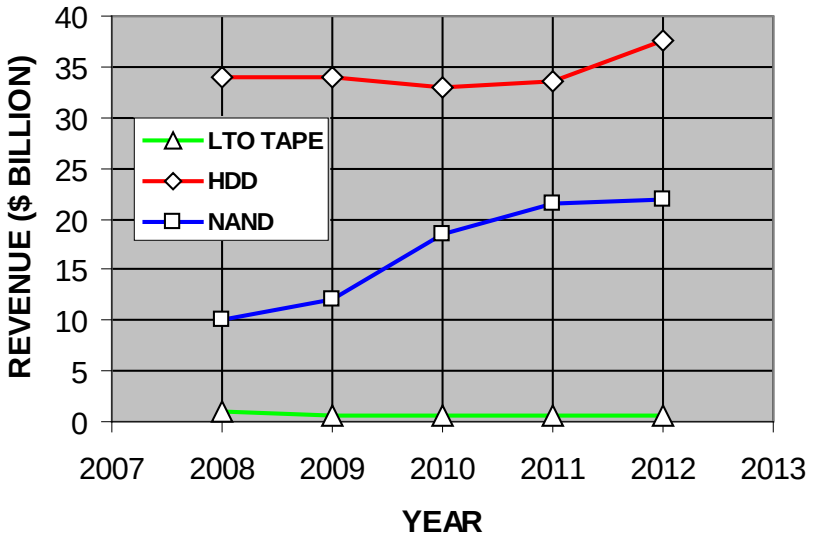
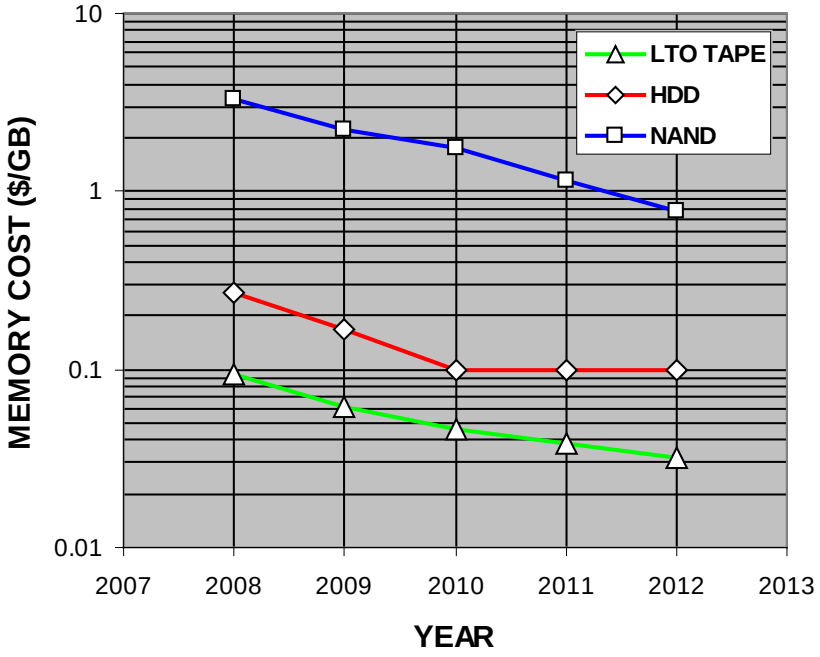
Cost of Storage

- In 2012 HDD showed a revenue increase which may likely be influenced by industry consolidation and industry shortages. The net results is that $/GB are stable for last two years
- In 2012 NAND showed dramatic $/GB drops, dramatic PB shipment increases but minimal increase in revenues





Summary – YE 2012 Numbers, Δ % Change from YE 2011

	NAND	HDD	LTO TAPE
PB Shipped	28000	380000	19500
MSI Produced	730	6950	210745
Areal Density	550 Gbit/in²	750 Gbit/in²	1.2 Gbit/in²
Revenue	$22.0 B	$37.5 B	$0.62 B
$/GB	$0.78	$0.10	$0.032

VALUES

	NAND	HDD	LTO TAPE
Δ PB Shipped	50%	13%	28%
Δ MSI Produced	50%	13%	28%
Δ Areal Density	0%	0%	0%
Δ Revenue	2%	12%	- 12%
Δ $/GB	- 33%	0%	- 16%

% DELTAS

BACKUP

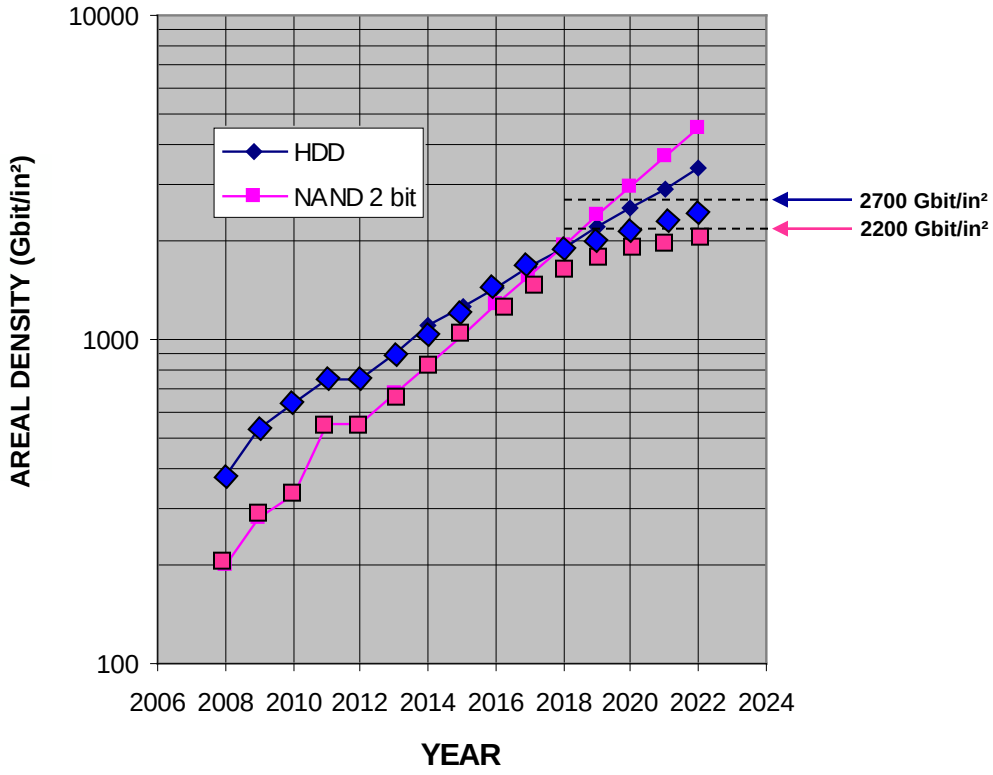
Lithography Projections

- Figure 8 from our 2013 MSST paper

Minimum feature size projections for HDD and NAND technologies. NAND technology data from ITRS 2012 final report. HDD projections from Fontana et. al., IEEE Trans. Mag.Vol. 48, No. 5, pp 1692-1696, 2012

A Future

- Assume HDD and NAND physics is limited to 10 nm features
  - NAND at 20 nm support 550 Gbit/in² ➔ NAND at 10 nm supports 2200 Gbit/in²
  - HDD patterned media with 16 nm islands and 25 nm cells supports 1000 Gbit/in² ➔ HDD patterned media with 10 nm islands and 15 nm cells supports 2700 Gbit/in²
  - HDD will approach this limit asymptotically at rates not exceeding 15% per year
  - NAND will approach this limit asymptotically at rates not exceeding 20% per year



4 Year History – PB, AD, Revenue

	YE 2008	YE2009	YE2010	YE2011	3 Year Percentage Growth
HDD					
Units (HDDs millions)	540	557	652	620	
PB Shipped (PB)	125000	200000	330000	335000	+ 268%
Areal Density (Gb/in²)	380	530	635	750	+ 200%
Revenue ($ billions)	34.0	34.0	33.0	33.5	- 2%
$/GB Shipped	0.272	0.170	0.100	0.100	
NAND					
Units (2GBs millions)	1500	2715	5232	9326	
PB Shipped (PB)	3000	5430	10464	18600	+ 620%
Areal Density (Gb/in²)	200	280	330	550	+ 275%
Revenue ($ billions)	10.0	12.1	18.5	21.5	+ 215%
$/GB Shipped	3.33	2.23	1.77	1.16	
LTO TAPE					
Units (Cart. millions)	20	24	25	25	
PB Shipped (PB)	10400	12165	15300	17800	+ 71%
Areal Density (Gb/in²)	0.9	0.9	1.2	1.2	+ 33%
Revenue ($ billions)	1.0	0.7	0.7	0.7	- 30%
$/GB Shipped	0.093	0.061	0.046	0.038	

-Consumer Base
-Thailand Floods
-Industry Consolidation
-50000 PB Enterprise

-Consumer Base
-Capital Investment
-20 nm Lithography
-1000 PB Enterprise

-No Consumer Base
-Rigid 2 Year Product Introduction Cycle
-17800 PB Enterprise