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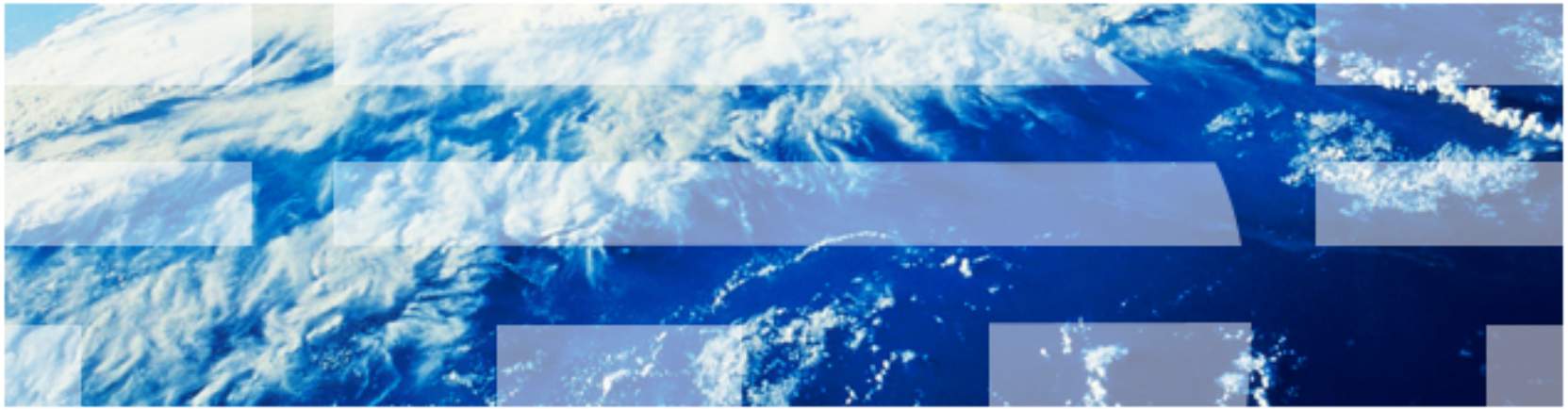
Storage Media Overview
Projecting Future Trends
from
2008-2015 Historic Perspectives



Outline

- A Definition: Storage Media is PB shipments for LTO TAPE, HDD, and NAND
- A Comment: Future Predictions are Difficult while Past Performance is Verifable
- Topics
  - Storage Landscape for 2008-2015
  - Moore's Law – Underachieving implies components are more valuable
  - Exabytes and Millions of Square Inches and Areal Density
  - Landscape Comparisons: 2008-2015, 2012-2015, 2015
  - MSI Examples and Specific Trends
  - Summary and the Future

Storage Landscape for HDD, TAPE, NAND: 2008-2015

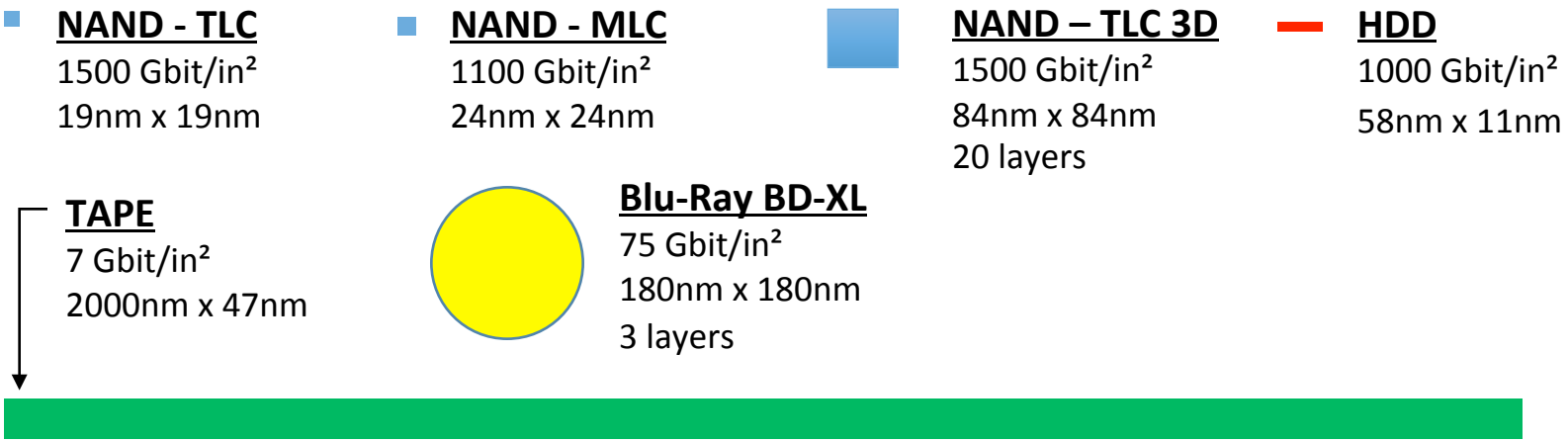
- The storage component landscape has been monitored by tracking annual revenue and technology trends in LTO TAPE MEDIA, HDD, and NAND
  - Areal density, Revenue
  - $/GB and Exabyte shipments
- 2015 observations
  - NAND: Significant EB growth but minimal revenue growth
  - HDD: Minimal EB growth with revenue decrease
  - LTO TAPE MEDIA: EB growth with lower revenue
  - **$/GB** for all technologies reduced by between 16% and 22%
  - **Areal Density** slowing for HDD
- Overview

2015 % CHANGE	EXABYTES	REVENUE	$/GB	AREAL DENSITY
LTO TAPE MEDIA	9.6%	-10.0%	-18.4%	100%*
HDD	2.9%	-15.3%	-16.4%	11%
NAND FLASH	32.8%	3.1%	-22.1%	25%
TOTAL	6.1%	-6.3%	NA	NA

***LT07 introduced late 2015 effectively doubling density but 2 year product cycle**

The Bit Cell Landscape

- Bit Cell Observations – "There is not much room at the bottom" for HDD and NAND



- NAND Strategy – Multilayer or 3D cells (larger cell area with multiple layers of cells)
- HDD Strategy – Smaller cell area using thermal writing of "harder" magnetic media
- TAPE Strategy – Moore's Law Scaling – "There is still room at the bottom"

Storage Landscape – 8 Year History

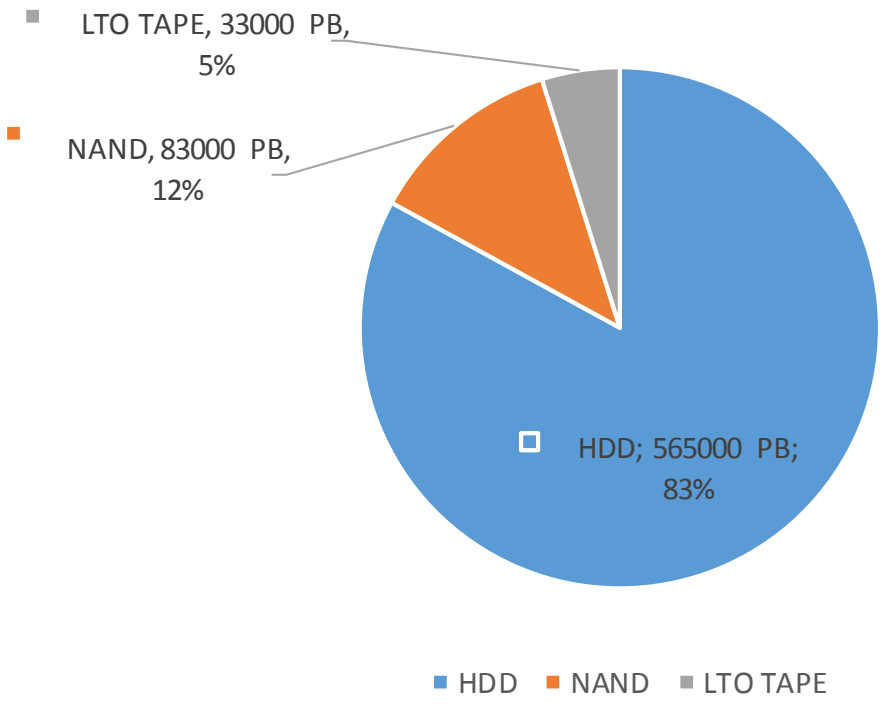
	2008	2009	2010	2011	2012	2013	2014	2015
HDD								
Units (HDD millions)	540	557	652	620	577	551	564	470
PB Shipped (PB)	125000	200000	330000	335000	380000	470000	549000	565000
Areal Density (Gb/in^2)	380	530	635	750	750	900	900	1000[1]
Revenue ($ billions)	34.0	34.0	33.0	33.5	37.5	33.4	33.4	28.3
$/GB Shipped	0.272	0.170	0.100	0.100	0.100	0.071	0.061	0.051
NAND								
Wafers (12" -- millions)	7.3	8.3	9.7	11.3	12.1	13.7	14.8	15.9
PB Shipped (PB)	3000	5430	10464	18600	28000	39000	62500	83000
Areal Density (Gb/in^2)	200	280	330	550	550	850	1200	1500
Revenue ($ billions)	10.1	12.1	18.5	21.5	22.0	24.0	32.2	33.2
$/GB Shipped	3.33	2.23	1.77	1.16	0.78	0.615	0.515	0.401
LTO TAPE MEDIA								
Units (Cart millions) [1]	27.1	24.3	25.0	24.3	23.4	21.6	22.2	19.4
PB Shipped (PB) [1]	11050	11960	15340	18420	20680	24270	30100	33020
Areal Density (Gb/in^2)	0.9	0.9	1.2	1.2	2.1	2.1	2.1	4.1
Revenue ($ billions) [2]	1.0	0.7	0.7	0.7	0.62	0.54	0.50	0.45
$/GB Shipped	0.0905	0.0585	0.0456	0.0380	0.0300	0.0222	0.0166	0.0134

1. 2.5" HDD areal density -- 1000 Gbit/in^2, 3.5" HDD areal density -- 800 Gbit/in^2 **2**. TAPE MEDIA PB / Cartridge data from LTO Consortium
3. LTO TAPE MEDIA revenue data from SCCG for 2008-2014 and extrapolated for 2015 using 7 year trend lines

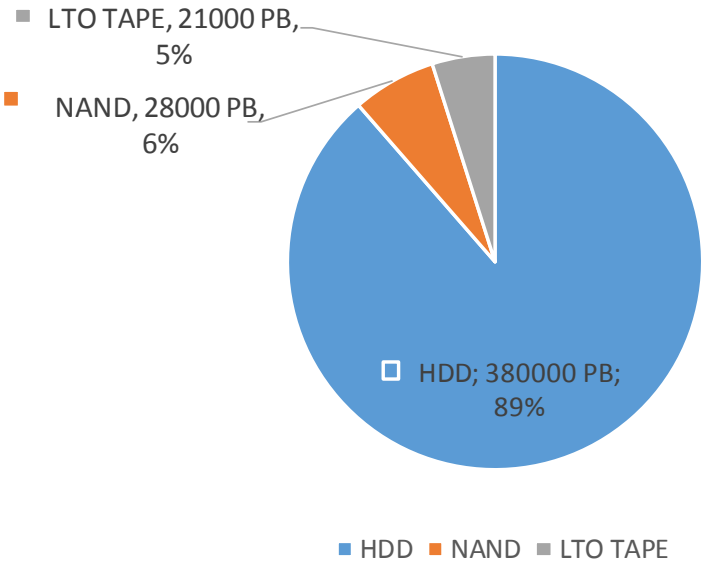
Storage Media Environment -- EB

- 2015 vs 2012 – NAND PB Market Share Increase, HDD PB Market Share Decrease

2015 PB Shipments – 681,000 PB



2012 PB Shipments – 429,000 PB



Storage Media – Exabytes, Areal Density, MSI Definitions

- Exabyte (EB) Shipments of Storage Media relies on a manufacturing base
  - NAND – 300 mm diameter wafer starts
  - HDD – Individual drive shipments with heads and disk surfaces
  - LTO TAPE – Cartridge shipments with meters of ½" tape width

- Increases in Exabyte Shipments of Storage Media comes from either increasing the factory capacity of the manufacturing base or by increasing the efficiency of storing more bits per unit surface area of manufactured media
  - Factory Capacity is Millions of Square Inches of manufactured media – MSI
  - Bits per Unit Area is Areal Density – AD or GB per square inch

- EB = MSI x AD and Revenue = EB x $/GB or Revenue = MSI x AD x $/GB

- Increase in EB shipments comes with cost: Factories for and MSI increase or R&D expenditures for an AD improvement.

- Issue: Areal Density and consequently $/GB metrics have underperformed in the last three years

Storage Media – Moore's Law Realities

- **Moore's** Law Perception
  - *$/GB decreases 30% per year or 50% every two years*
  - *AD increases 40% per year or 100% every two years*
  - NET == Every 2 years the component manufacturers sell 2X more storage media for 0.5X less cost per bit for a revenue neutral position. Revenue increases only if manufacturing investment (MSI) increases or if |$/GB| reductions decreases

- **Moore's** Law Reality
  - $/GB decreased ~ 20% / yr for the three year period 2013 – 2015
  - Areal Density ~ 40% / yr for NAND, 26% / yr for LTO TAPE, 10% / yr for HDD for the three year period 2013-2105

- **Consequences** of Moore's Law ($/GB) Underachieving (HDD – 20%/yr vs 30%/yr)
  - Storage is more valuable; less easily replaced – 62% increase in replacement cost

	4 TB Drive	10 PB System
2016 Cost	$160	$400K
2020 Cost (20%/yr $/GB Decrease)	$65	$162K
2020 Cost (30%/yr $/GB Decrease)	$40 (Moore's Law)	$100K (Moore's Law)

Storage Media Comparisons: 2008 – 2015, 2012 – 2015, and 2015

- Moore's Law not achieved: i.e. Density increasing at 40%/YR and $/GB reducing at 30%/YR
- Storage is more valuable, less replaceable, and must be reliable for longer time periods

	Annual Change – last 8 years	Annual Change -- last 3 years	Annual Change – last year
NAND $/GB	-26%	-20%	-22%
HDD $/GB	-21%	-20%	-16%
TAPE $/GB	-24%	-23%	-19%
NAND EB Ships	+61%	+43%	+33%
HDD EB Ships	+24%	+14%	+3%
TAPE EB Ships	+17%	+17%	+10%
NAND Revenue	+19%	+15%	+3%
HDD Revenue	-3%	-9%	-15%
TAPE Revenue	-8%	-9%	-10%
NAND AD	+33%	+39%	+25%
HDD AD	+15%	+10%	+11%
TAPE AD	+25%	+26%	+100%

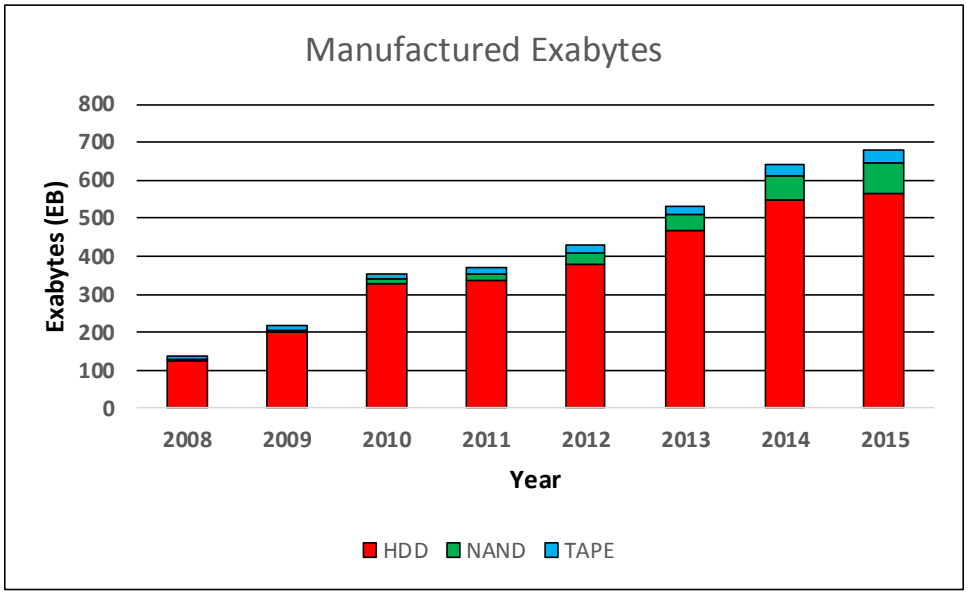
Moore's Law – -30%/YR

Issue--Revenue Decrease
|$/GB| decrease
≥
|EB| increase

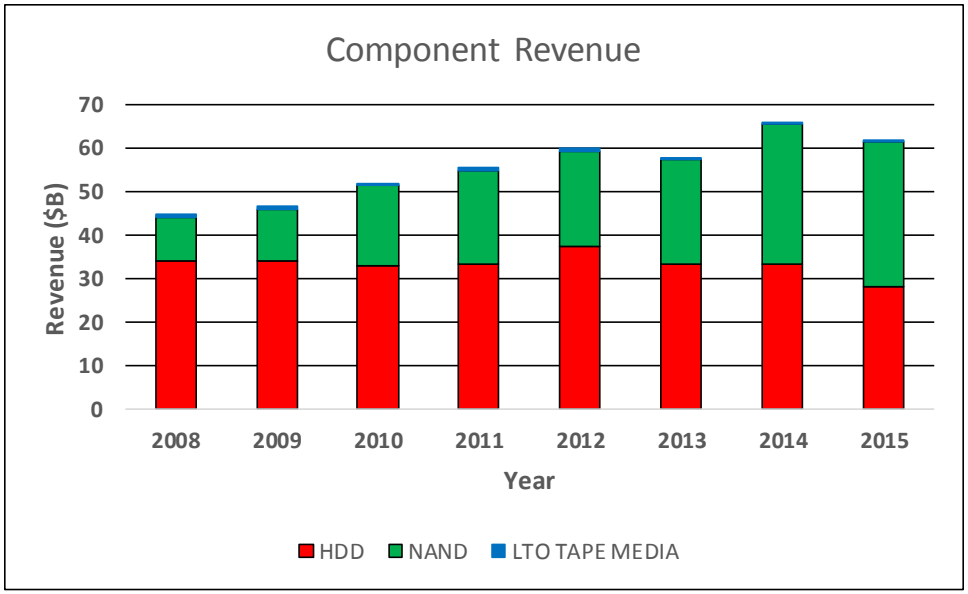
Moore's Law – +40%/YR

Two Contrarian Trends from 2015 Data

- Total annual manufactured Exabytes shows a linear trend (i.e. not exponential) with an annual increase over the last 8 years of 77 EB / YR ($r^2 = 0.98$)



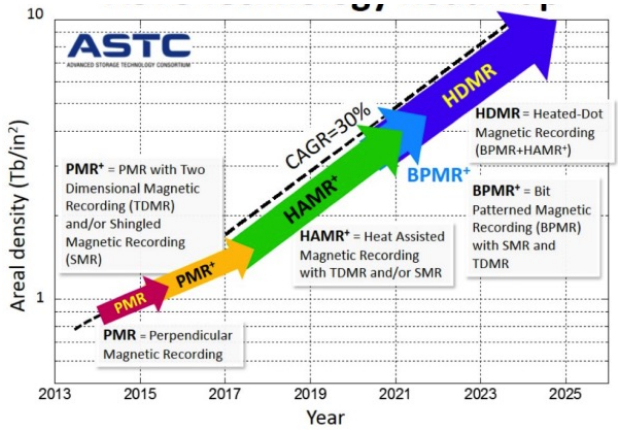
- Total revenue for manufactured Exabytes is stable, i.e. no growth, with decline in HDD revenue absorbed by increase in NAND revenue



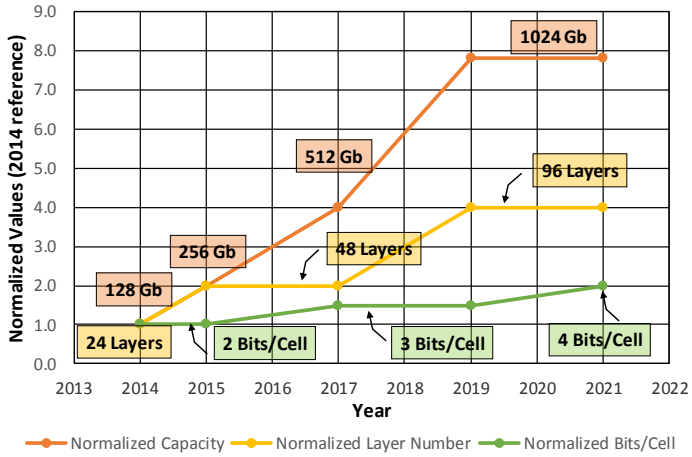
Areal Density Roadmaps Not Being Updated

- Technology consortiums are less relevant to industrial du-opolies or tri-opolies
- Areal density increases are more difficult, 40% annual growth no longer achievable
- Areal density roadmaps being are replaced by capacity roadmaps, i.e. what clients buy

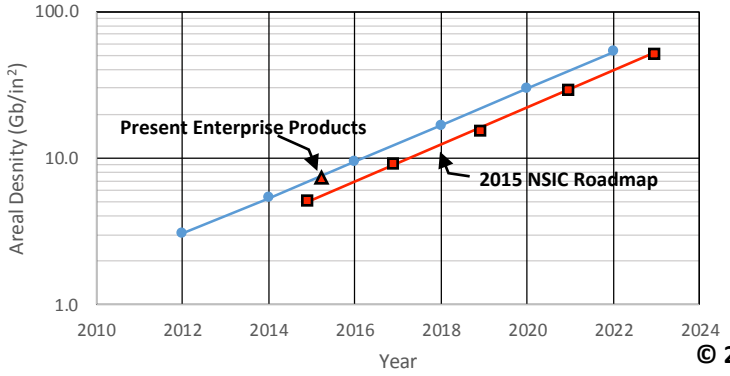
▪ HDD: source ASTC 2013



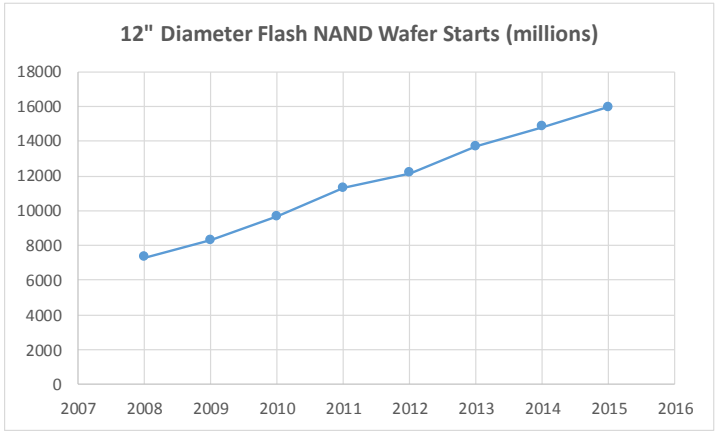
▪ NAND: source ITRS 2013

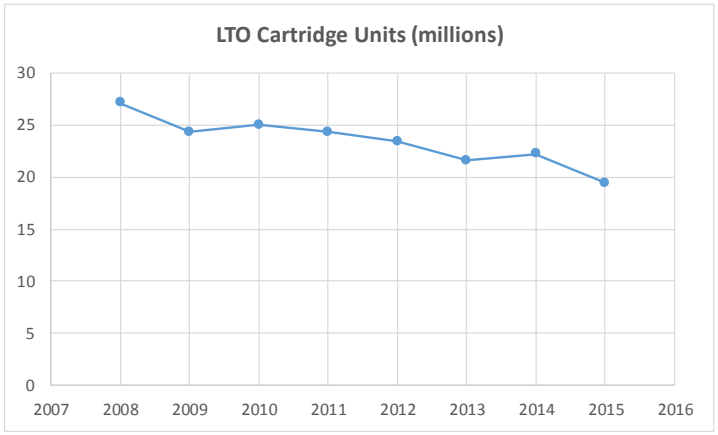


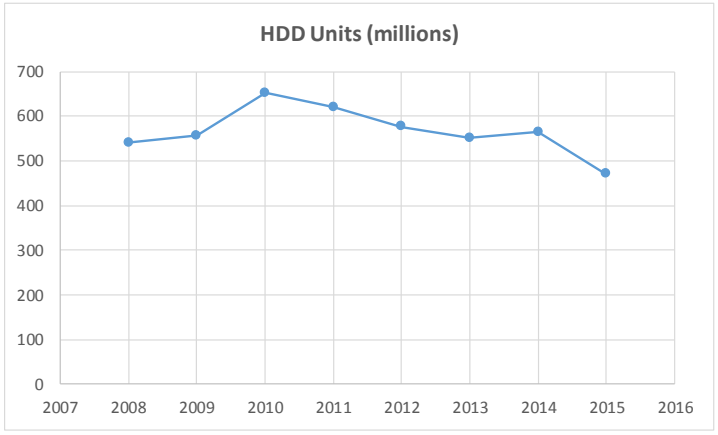
▪ TAPE: source NSIC 2013



Revisiting MSI (millions of square inches) for Storage Components



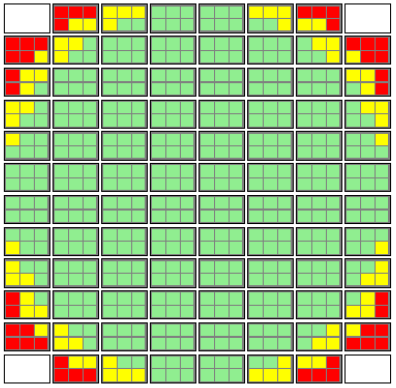


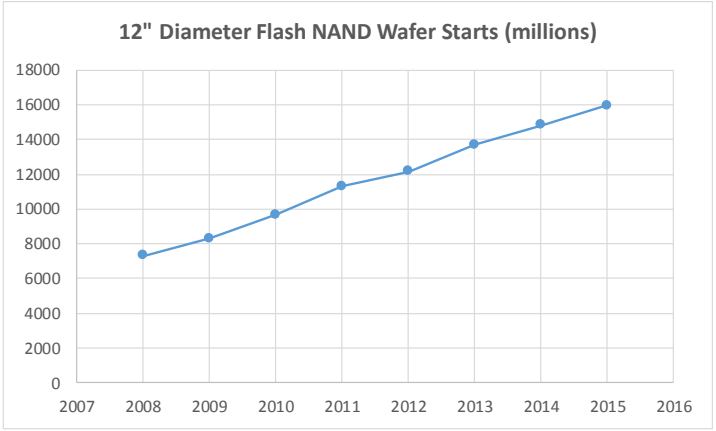


- One measure of storage growth is MSI or millions of square inches of annually manufactured storage media.
- Any increase in MSI capability requires capital investment
- An increase in EB or PB memory shipments is a product of increased MSI and AD or areal density (i.e. the number of bits that a memory technology supports per unit area)
- In 2015 LTO Media, HDD, and NAND all increased EB memory shipments but only NAND increased MSI
  - NAND MSI (wafer starts): + 7%
  - HDD MSI (drives shipped): -17%
  - LTO MSI (cartridge shipped): -12%
- NAND investment in MSI reflects on NAND increases (35%) in Exabyte shipments of memory

2015 NAND MSI Observations

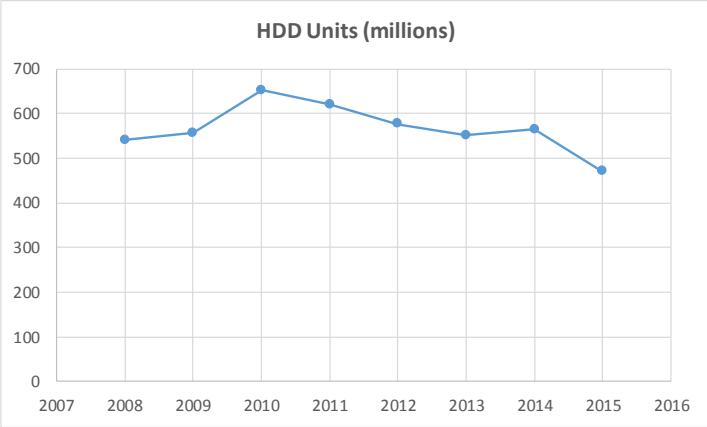
- Landscape: 16,000,000 wafers, 83,000 PB, $33B Revenue
  - $0.401 / GB or $2075 / wafer
  - 5.187 TB / wafer
  - 11.7 GB/ chip (440 12 mm x 12 mm chips per wafer)
  - State of art chip is ~ 3X greater or 32 GB (375 chips 13 mm x 13 mm per wafer) or 12.0 TB / wafer
- Factories
  - $8B state of art facility can produce 4000 wafers / day or 1.4M wafers / yr or up to 16,000 PB / yr
  - NAND wafer capacity increased at a linear rate of ~ 1,000,000 per year implying annual new factory investment of ~ $6B/year
  - Without any increase in areal density, a doubling of PB output for NAND would require 6 new factories and a $48B investment.
- An MSI Example
  - Using best of breed chip (12 TB/wafer) would require 47 M wafers to replace 565 EB of HDD storage
  - 47 M wafers requires 32 $9B factories or $288B in Capital!! ➔ areal density is a better strategy!!!





2015 HDD MSI Observations

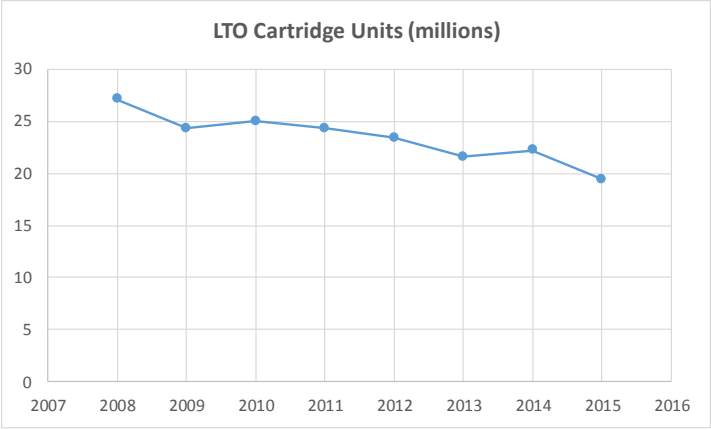
- 2015 Landscape:
  - 470,000,000 drives
  - 565,000 PB
  - $28.3B Revenue
  - $0.051 / GB
  - $60.2 / drive
  - 1.2 TB / HDD
- 2014 Landscape:
  - 564,000,000 drives,
  - 549,000 PB,
  - $33.4B Revenue
  - $0.061 / GB
  - $59.2 / drive
  - 1.0 TB / HDD



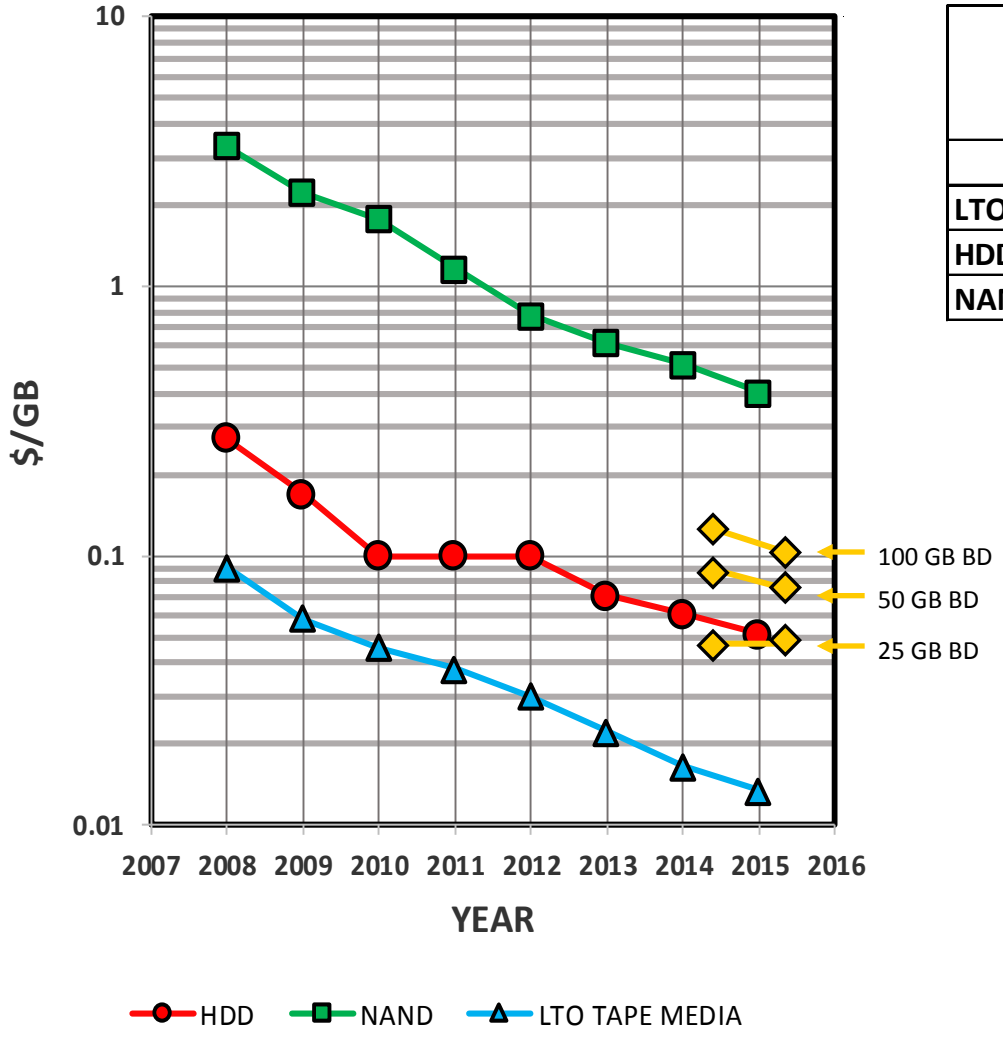
- 3% more PB, and 17% lower $/GB implies ~ 15% less revenue
- The 20% increase in TB/HDD not resulting solely from areal density increases
  - Areal density increase only 10%
  - Product mix shift from 2.5” HDD to 3.5” HDD (more surface area and more MSI)
  - More platters / HDD (more surface area and more MSI)
- MSI (i.e. number of platters and number of heads) may have decreased in 2015

2015 LTO TAPE Media MSI Observations

- Landscape: 19,400,000 cartridges, 33,000 PB, $0.45B Media Revenue
  - $0.0134 / GB
  - $23.20 / cartridge
  - 1.7 TB / cartridge (reflective of LTO product mix)
  - Note: LTO5 capacity 1.5 TB, LTO6 capacity 2.5 TB, LTO7 capacity 6.0 TB (4Q15 introduction)
- An MSI Example
  - Media Capacity is 19.4M cartridges
  - Maximum cartridge capacity is 6 TB
  - LTO PB shipments could increase from 33,000 to 116,000 PB shipments with no new capital investment



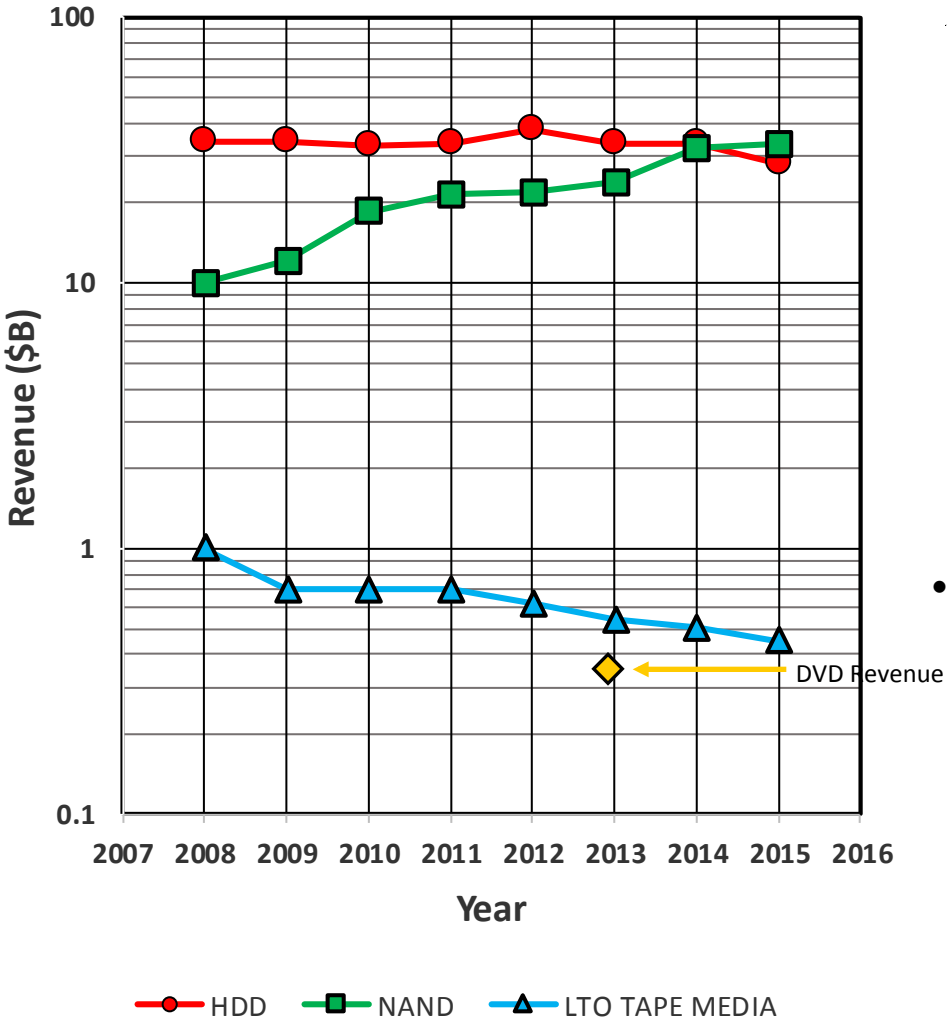
$/GB Trends: 2008-2015



$/GB	2014	2015	1 YEAR % Δ	8 YEAR ANNUAL % Δ
LTO TAPE MEDIA	0.0166	0.0134	-19.3%	-23.9%
HDD	0.061	0.051	-16.4%	-21.3%
NAND	0.515	0.401	-22.1%	-26.1%

- Observations
  - $/GB reduction is least for HDD
  - Relative to 8 year annual averages, 2015 $/GB reductions are less
  - $/GB data for Blu-ray data disc, i.e. BD-RE, are not available for large quantities so optical component comparisons are not possible. Note "upside down" $/GB pricing for disk capacities (quantities of ~ 20) with no decrease for 25 GB BD but drop in 100 GB BD.

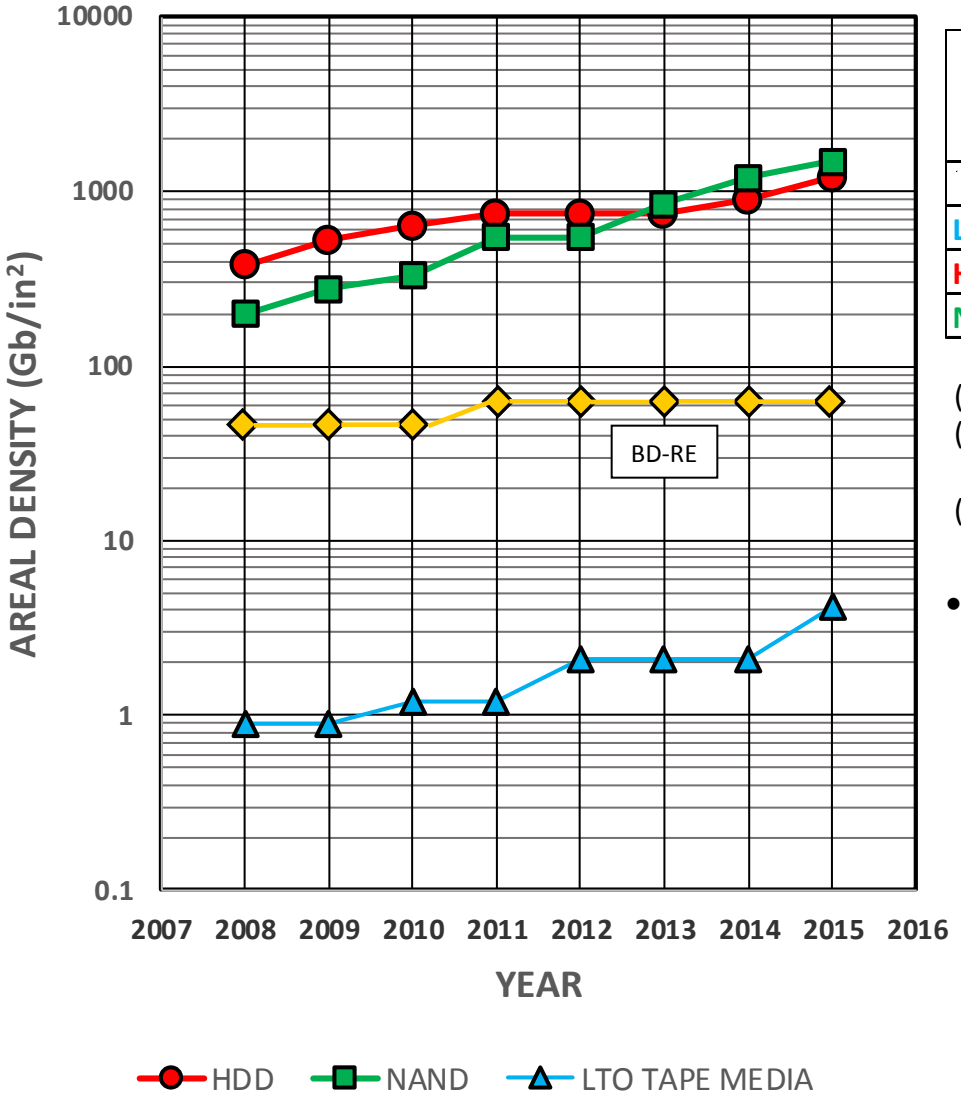
Revenue Trends: 2008-2015



Revenue ($B)	2014	2015	1 YEAR % Δ	8 YEAR ANNUAL % Δ
LTO TAPE MEDIA	0.5	0.45	-10.0%	-8.4%
HDD	33.4	28.3	-15.3%	-2.6%
NAND	32.2	33.2	3.1%	18.5%
TOTAL REVENUE	66.1	61.95	-6.3%	4.7%

- Observations
  - NAND revenue exceeds HDD for first time
  - Significant HDD revenue decrease leads to overall drop in total component revenue for all storage technologies
  - Significant NAND revenue growth above historical averages
  - LTO TAPE cartridge revenue continues decline in the 8% to 10% annual rate range

Maximum Areal Density Trends: 2008-2015

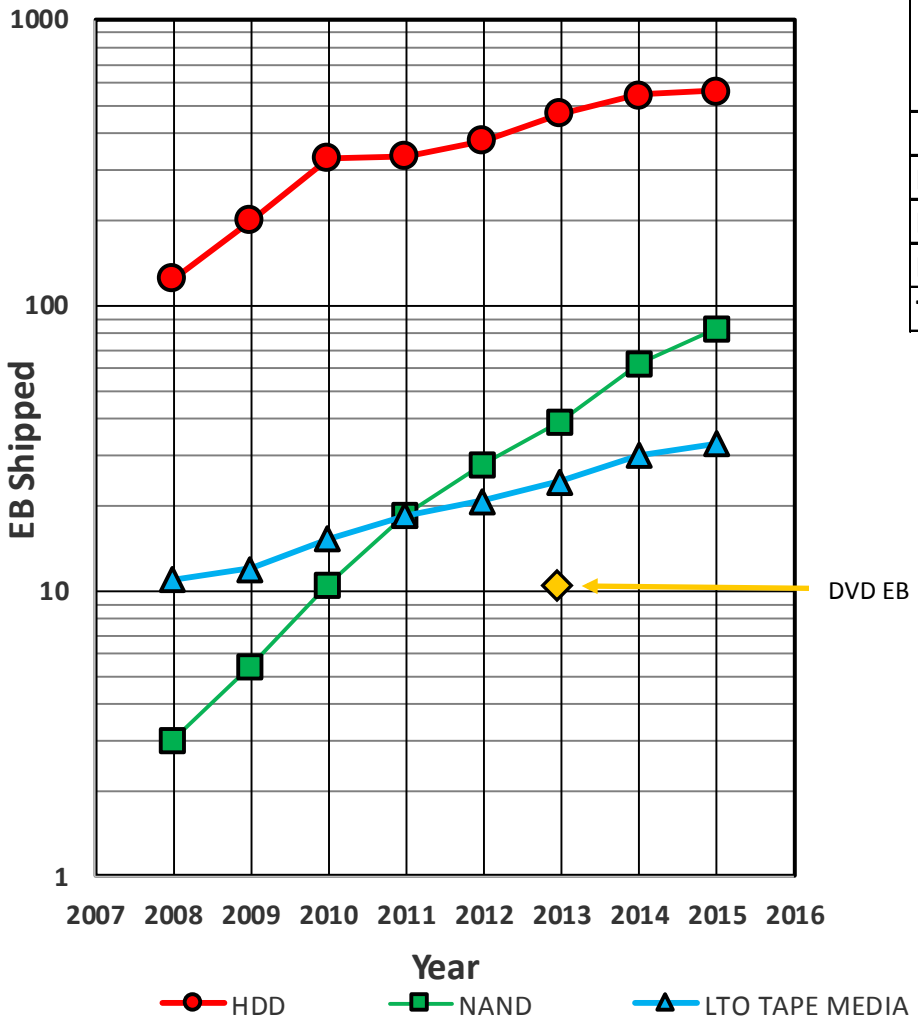


AREAL DENSITY (Gb/in²)	2014	2015	1 YEAR % Δ	7 YEAR ANNUAL % Δ	
LTO TAPE MEDIA	2.1	4.3	104.8%	25.0%	(1)
HDD	900	1000	11.1%	14.8%	(2)
NAND	1200	1500	25.0%	33.4%	(3)

(1) LTO7 introduced YE2015
(2) HDD density increase represents shingle magnetic recording – 800 Gb/in² for 3.5" HDD and 1000 Gb/in² for 2.5" HDD
(3) NAND density increase represents TLC (3 bit/cell) at 16 nm, $5F^2$ cell

- Comments
  - LTO areal density tracking is straightforward
  - HDD areal densities are the maximum reported in 2.5" HDDs. Note, that maximum areal density reported in 3.5" HDDs in in the 800 Gbit/in² range.
  - NAND areal density difficult to determine since the classic $4F^2$ cell design is not rigorously used.

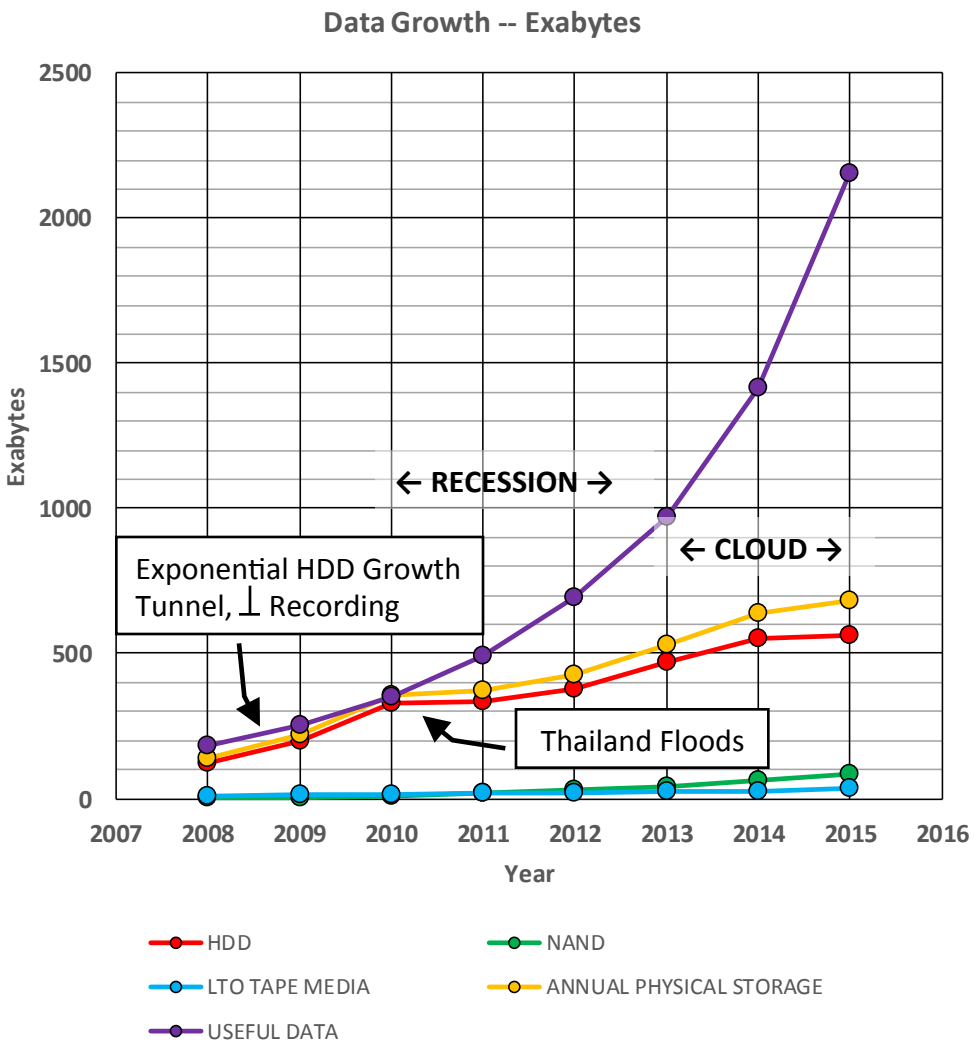
Exabyte Shipment Trends: 2008-2015



EB SHIPPED	2014	2015	1 YEAR % Δ	8 YEAR ANNUAL % Δ
LTO TAPE MEDIA	30.1	33.0	9.6%	16.9%
HDD	549.0	565.0	2.9%	24.0%
NAND	62.5	83.0	32.8%	60.7%
TOTAL EB SHIPPED	641.6	681.0	6.1%	25.6%

- Observations
  - HDD EB shipment increase **significantly less** than historical average
  - LTO Media EB shipment increase is less than historical average
  - Significant NAND EB shipment increase relative to LTO TAPE and HDD.
  - NAND EB shipments exceed LTO EB shipments (consumer market, i.e. IPhone6) by > 2X
  - Total EB shipped grew only by 6%!!!

Data Creation and Storage Manufacturing



- Observations
  - Total manufactured storage in 2015 was 681 EB, an increase of 6% over 2014 manufactured storage EB
  - Contrast these values with 2013 IDC claims that created **useful** data in 2015 would be 2180 EB, an increase of 40% over 2014 created **useful** data, and that useful data would continue to grow at 40% annually.
  - **Issue 1**: Shortfall between physical storage manufactured in 2015 vs useful data created in 2015 is 1500 EB (2X more than all storage manufactured in 2015). Some shortfall is absorbed by de-duplication and by compression.
  - **Issue 2:** Manufactured storage is growing by at best 6% per year vs perceived data grown of 40% year.
  - **Issue 3:** In view of Issue 1 and Issue 2, either the IDC forecasts are not accurate or storage users are selectively storing data
  - **Issue 4:** Manufactured storage (with the exception of 2008-2010) is not increasing geometrically

Summary

- Changing NAND environment – Oversupply
  - 2015: 30% increase in PB shipments with 3% increase in revenue
  - 2014: 60% increase in PB shipments with 30% increase in revenue
- Changing HDD environment – Market Erosion
  - 2015: 3% increase in PB shipments with **15% decrease** in revenue
  - 2014: 17% increase in PB shipments with 0% revenue change
- Changing LTO Media environment – Continuing Revenue Drop ~ 8%/YR to 10%/YR
- NAND revenue exceeds HDD revenue; NAND areal density exceeds HDD areal density
- Manufacturing environment – Moore's Law "doubling" not achieved
  - Revenue for manufactured PB of storage **decreased by 6%**
  - Total manufactured PB only increased by 6% in 2015. A direct conflict with the perception that useful data increases at 40% annually.
- Technology
  - TAPE – Next generation sensor introduction -- **Moore's Law Scaling**
  - HDD – HAMR, Shingle Magnetic Recording, More Platters – **Not Moore's Law Scaling**
  - NAND – Planar 3 bit/cell designs at < 16 nm, 3D multi-layer cells at ~ 60 nm – **Not Sustained Moore's Law Scaling (24 layers to 48 layers to 96 layers to …)**

Summary — (Four Year Horizon) Future

- NAND environment
  - 3.00X density improvement means moving from 36 layers to 108 layers
  - 1.33X density improvement means moving from 3 bits per cell to 4 bits per cell
  - Net: In a 4 year horizon, anticipate $/GB dropping by 4X **($0.10/GB)**

- LTO Tape
  - Introduction of advanced transducers and evolutionary development in BaFe media assures a 4X density improvement. 2 um track pitches go to 0.5 um track pitches.
  - Advances are TPI (tracks per inch) intensive and rely on Moore's Law Scaling.
  - Net: in a 4 year horizon, anticipate $/GB dropping by 4X **($0.0035/GB)**

- HDD
  - 10% annual areal density increases imply only a 1.45X density increase or $/GB dropping by only 0.7X. **($0.035/GB -- likely high since major shift to large capacity lower cost drives)**
  - Net: New technologies are not Moore's Law driven and not extendable (e.g HAMR, 2D)

- Economic Implications in 4 years
  - Constant NAND component revenue requires 4X EB shipment increase to 320 EB (60% of HDD 2015 EB output)
  - Continued annual NAND wafer capacity increases of 6%/yr imply 2020 EB shipments > 400 EB
  - NAND is positioned for EB growth (Areal Density and MSI Growth) 

Summary — Technology and the Market

- NAND environment