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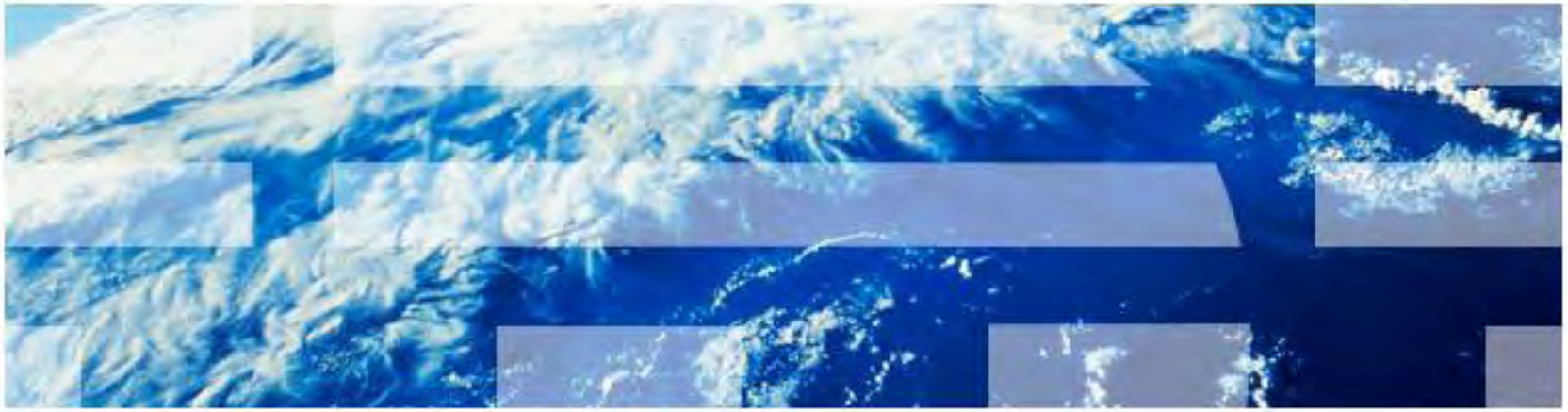
Storage Media Overview: Historic Perspectives
--2012 vs 2015 Comparisons
--2015 Trends



Outline

- A Definition: Storage Media is PB shipments for LTO TAPE, HDD, and NAND
- Topics
  - Storage Landscape for 2008-2015
  - Exabytes and Millions of Square Inches and Areal Density
  - Landscape Comparisons: 2009-2012 vs 2012-2015
  - MSI Examples
  - 8 Year Trends vs 2015 Trends
  - Summary

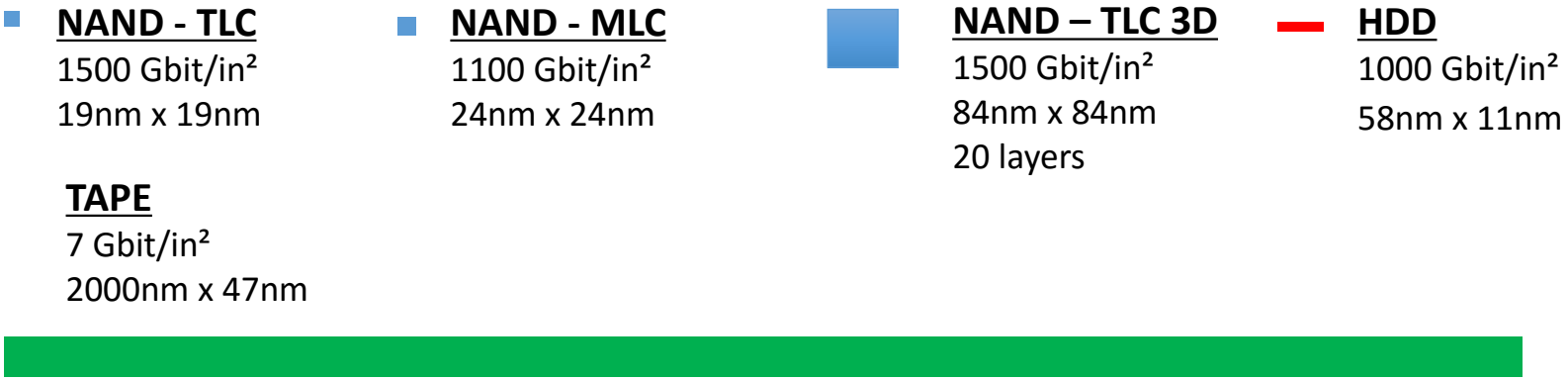
Storage Landscape for HDD, TAPE, NAND: 2008-2015

- The storage component landscape can be 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 were reduced by between 16% and 22%
- Overview

2015 % CHANGE	EB	REVENUE	$/GB
LTO TAPE MEDIA	9.6%	-10.0%	-18.4%
HDD	2.9%	-15.3%	-16.4%
NAND	32.8%	3.1%	-22.1%
TOTAL	6.1%	-6.3%	NA

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”

Data Sources and Data Methodology

- HDD Data:
  - WDC and Seagate: Quarterly Financial Reports
  - Toshiba: Scale data from WDC and Seagate using TAM (total available market) percentages reported by Seagate and WDC
  - $/GB is a “blended” value for all drive types from Total Revenue / Total EB Shipped
- NAND Data:
  - EB Shipments: Samsung presentations
  - Revenue: Quarterly summaries from DRAM EXCHANGE
  - $/GB is a “blended” value for all chip capacities and all bit / cell designs (SLC, MLC, TLC) from Total Revenue / Total EB Shipped
- LTO Media Data
  - 2008-2014: Santa Clara Consulting Group (SCCG) for Revenue and $/GB
  - 2015: No SCCG data for revenue, use 7 year trend line for 2015 estimate
  - 2008-2015: LTO cartridge number and LTO EB from LTO Consortium
  - $/GB is a “blended” value for all capacities from Total Revenue / Total EB Shipped

Storage Landscape – 8 Year History

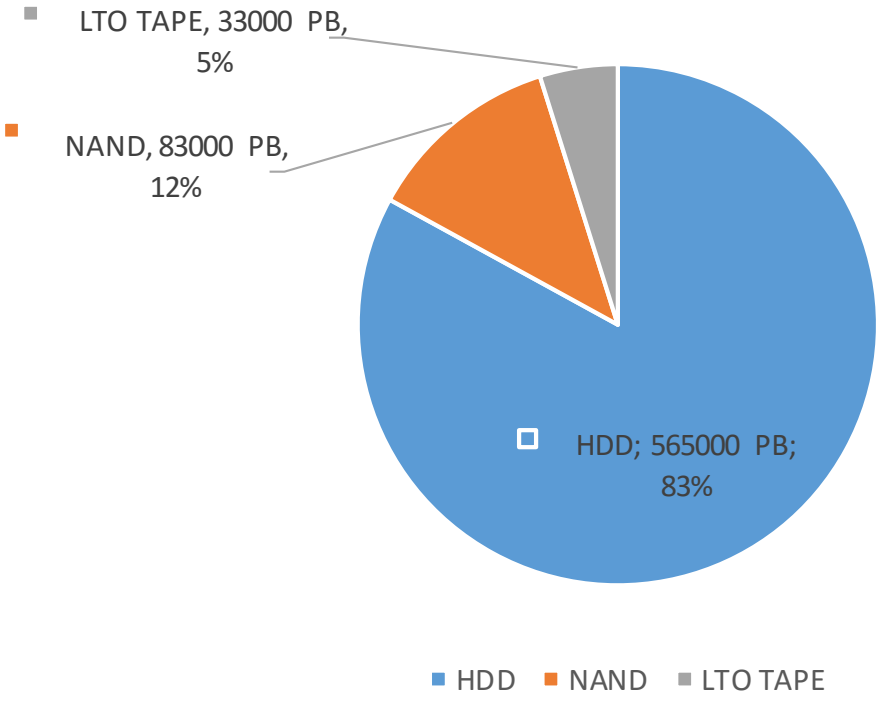
	2008	2009	2010	2011	2012	2013	2014	2015
HDD								
Units (HDD millions)	540	557	652	620	577	551	564	470
PB Shipped (PB)	125000	200000	330000	335000	380000	470000	549000	565000
Areal Density (Gb/in^2)	380	530	635	750	750	900	900	1000[1]
Revenue ($ billions)	34.0	34.0	33.0	33.5	37.5	33.4	33.4	28.3
$/GB Shipped	0.272	0.170	0.100	0.100	0.100	0.071	0.061	0.051
NAND								
Wafers (12” -- millions)	7.3	8.3	9.7	11.3	12.1	13.7	14.8	15.9
PB Shipped (PB)	3000	5430	10464	18600	28000	39000	62500	83000
Areal Density (Gb/in^2)	200	280	330	550	550	850	1200	1500
Revenue ($ 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

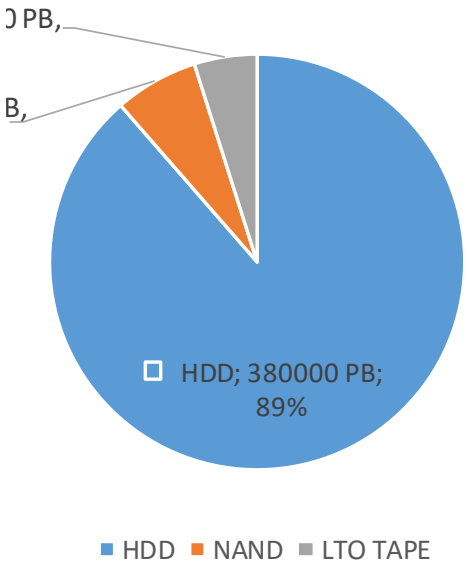
Storage Media Environment -- EB

- 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

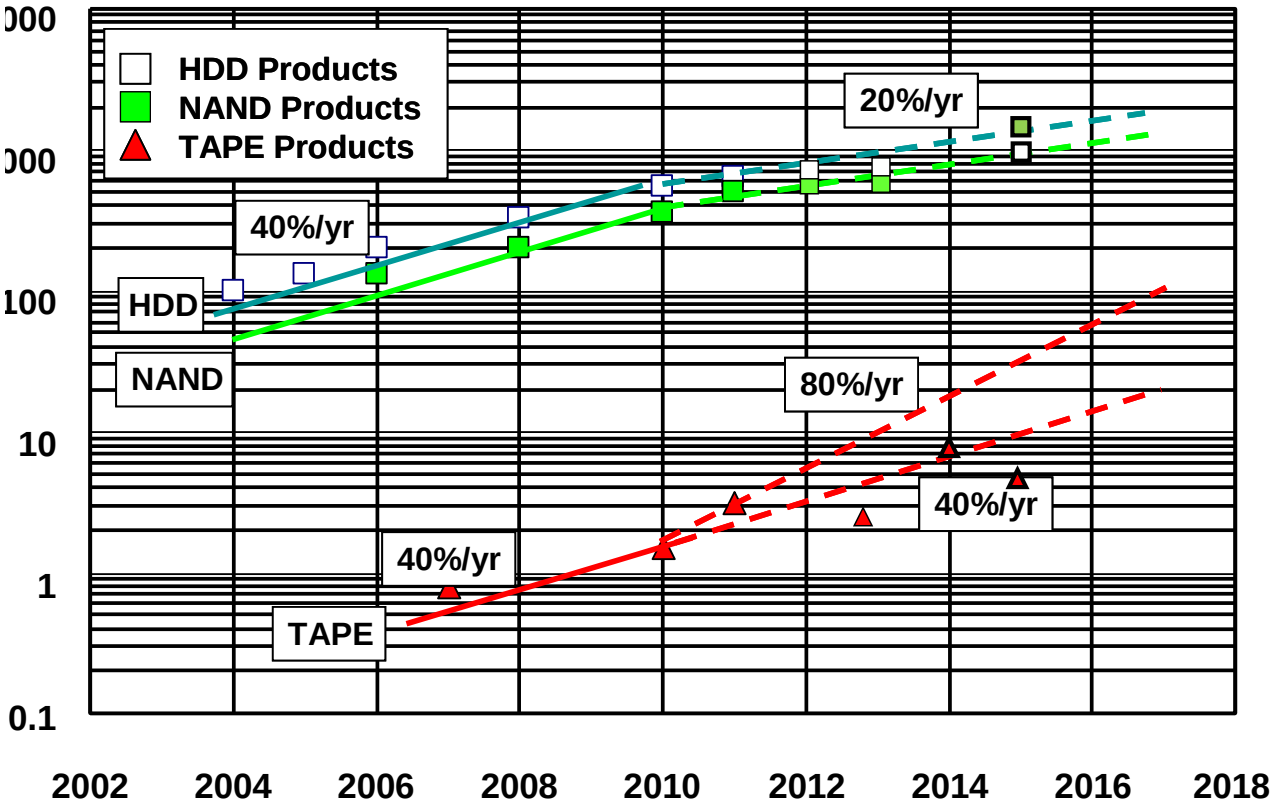
- EB = MSI x AD and Revenue = EB x $/GB or Revenue = MSI x AD x $/GB

- 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

MSST 2013 Slide -- Areal Density Projections Revisited

	2013 Projection for 2015 AD	Actual 2015 AD	Issue
HDD	20% / YR	10% / YR	No HAMR, Smaller AD than NAND!!
NAND	20% / YR	40% / YR	Adoption of MLC/TLC, AD > HDD!!
TAPE	40% - 80% / YR	30% / YR	Granularity, LTO vs Enterprise Products



Storage Media – Realities

- **Moore's** Law Historic 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

- $/GB Reality Perspective for the three year period 2012-2015
  - $/GB decreased ~ 20% / yr for the three year period 2013 – 2015 ➔ not 30% / yr
  - Total Storage Media revenue was constant

- AD Reality Perspective for the three year period 2012-2015
  - AD increased 40% / yr for NAND (MLC to TLC),
  - AD increased 26% / yr for LTO (LTO6 to LTO7),
  - AD increased 10% / yr for HDD (HAMR not in products)

Storage Media Comparisons – 2009 – 2012, 2012 – 2015, and 2015

- 2012-2015 Areal Density: Mixed performance for 40%/yr goal
- 2012-2015 $/GB: No technology meets 30%/yr reduction goal
- 2012-2015 Revenue: NAND at +15%/yr, HDD and LTO Tape Media at -9%/yr

	Annual Δ 2009-2012	Annual Δ 2012-2015	1 Year Δ 2015
NAND AD	25% / YR	39% / YR	25% / YR
HDD AD	12% / YR	10% / YR	11% / YR
LTO AD	32% / YR	26% / YR	100% / YR

	Annual Δ 2009-2012	Annual Δ 2012-2015	1 Year Δ 2015
NAND $/GB	-29% / YR	-20% / YR	-22% / YR
HDD $/GB	-16% / YR	-20% / YR	-16% / YR
LTO $/GB [2]	-20% / YR	-23% / YR	-19%/ YR

	Annual Δ 2009-2012	Annual Δ 2012-2015	1 Year Δ 2015
NAND Revenue	22% / YR	15% / YR	3% / YR
HDD Revenue	3% / YR	-9% / YR	-15% / YR
LTO Revenue [1]	-3% / YR	-9% / YR	-10% / YR

	Annual Δ 2009-2012	Annual Δ 2012-2015	1 Year Δ 2015
NAND EB	72% / YR	43% / YR	33% / YR
HDD EB	14% / YR	14% / YR	3% / YR
LTO EB [3]	20% / YR	17% / YR	10% / YR

1. 2015 LTO revenue data extrapolated from SCCG 7 year trends

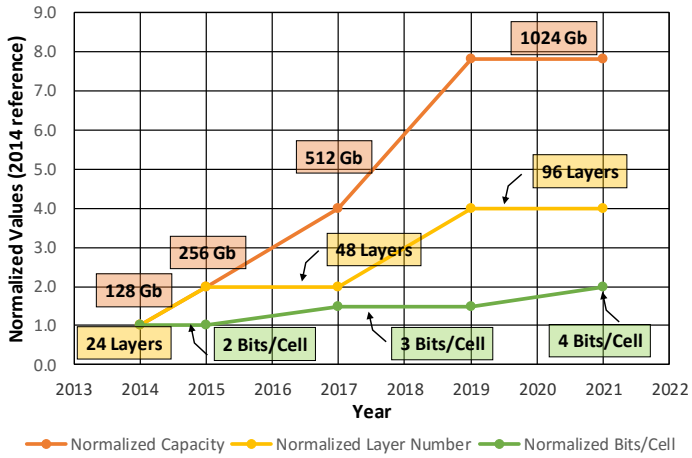
2. LTO $/GB data uses SCCG revenue data and LTO EB data, **3**. LTO EB data

Areal Density Roadmaps Not Being Updated

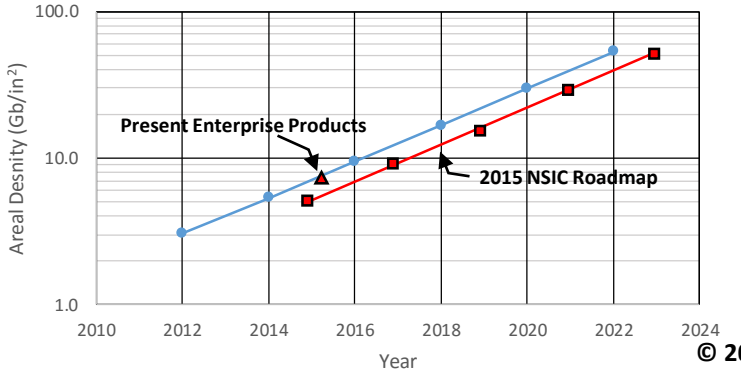
- Technology consortiums are less relevant to industrial du-opolies or tri-opolies
- Areal density increases are more difficult, 40% annual growth no longer achievable
- Areal density roadmaps being are replaced by capacity roadmaps, i.e. what clients buy

▪ HDD: source ASTC 2013

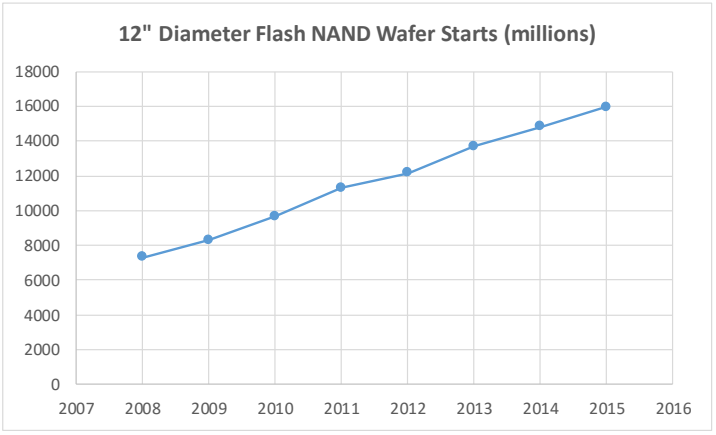
▪ NAND: source ITRS 2013

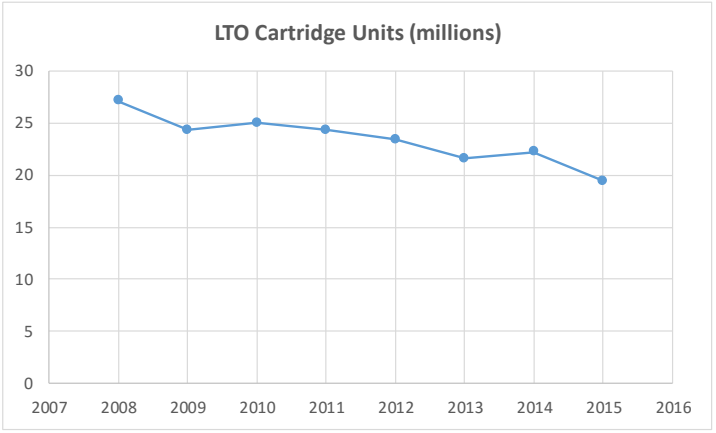


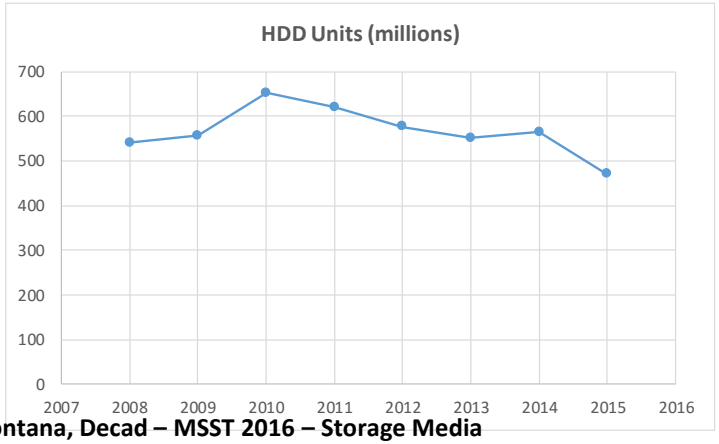
▪ TAPE: source NSIC 2013



Revisiting MSI (millions of square inches) for Storage Components



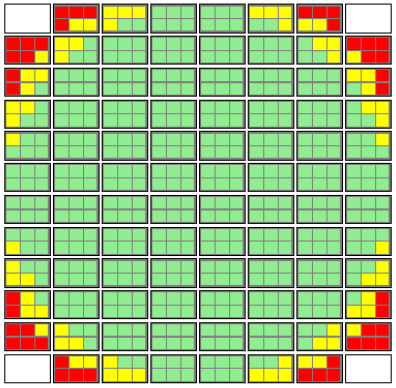


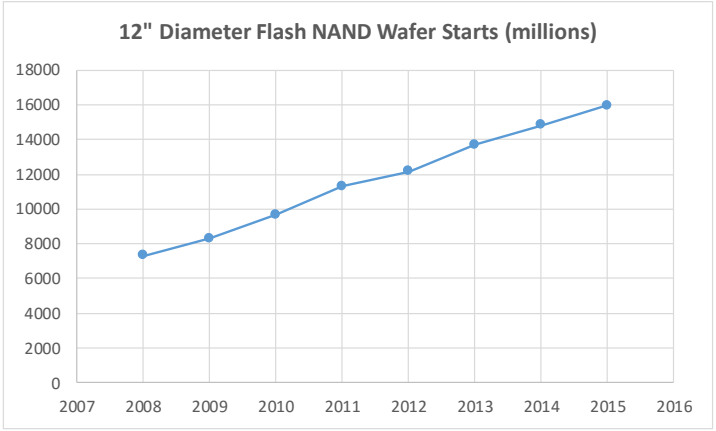


- One measure of storage growth is MSI or millions of square inches of annually manufactured storage media.
- Any increase in MSI capability requires capital investment
- An increase in EB or PB memory shipments is a product of increased MSI and AD or areal density (i.e. the number of bits that a memory 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

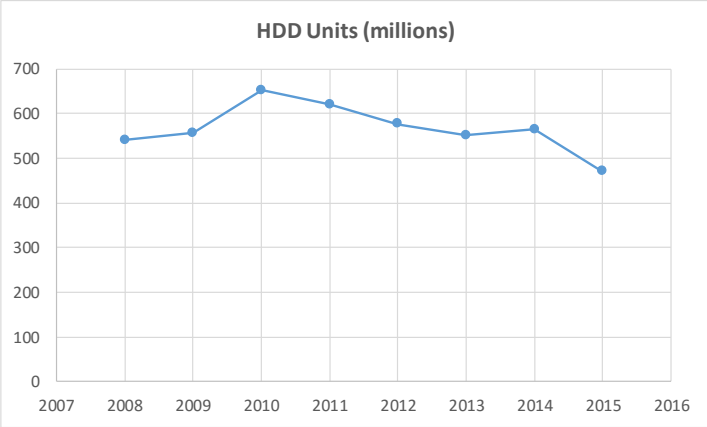
- Landscape: 16,000,000 wafers, 83,000 PB, $33B Revenue
  - $0.401 / GB or $2075 / wafer
  - 5.187 TB / wafer
  - 11.7 GB/ chip (440 12 mm x 12 mm chips per wafer)
  - State of art chip is ~ 3X greater or 32 GB (375 chips 13 mm x 13 mm per wafer) or 12.0 TB / wafer
- Factories
  - $8B state of art facility 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

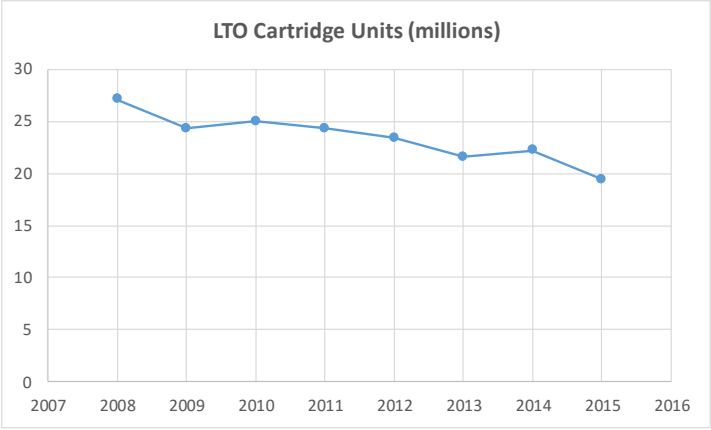
- 2015 Landscape:
  - 470,000,000 drives
  - 565,000 PB
  - $28.3B Revenue
  - $0.051 / GB
  - $60.2 / drive
  - 1.2 TB / HDD
- 2014 Landscape:
  - 564,000,000 drives,
  - 549,000 PB,
  - $33.4B Revenue
  - $0.061 / GB
  - $59.2 / drive
  - 1.0 TB / HDD



- 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

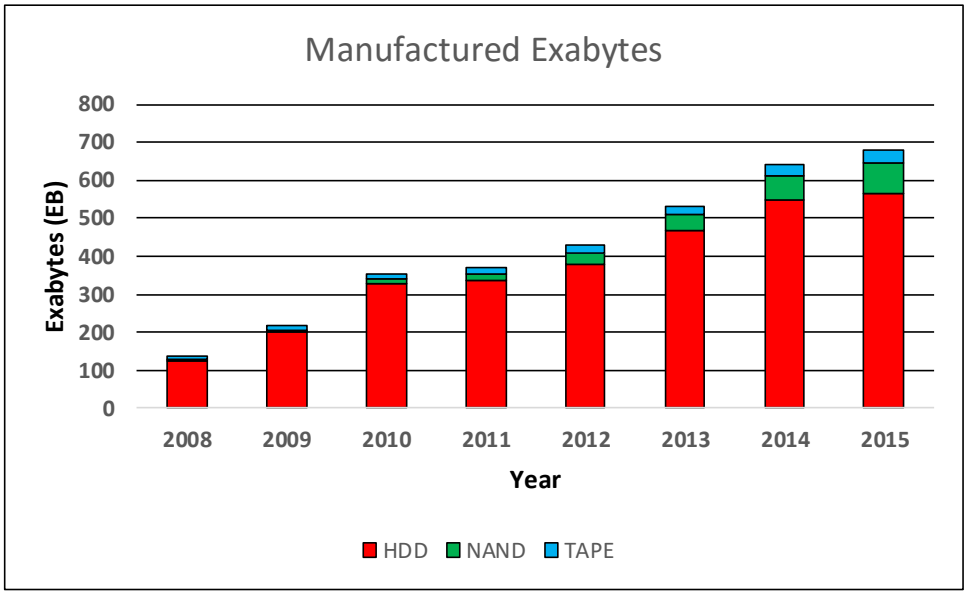
2015 LTO TAPE Media MSI Observations

- 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

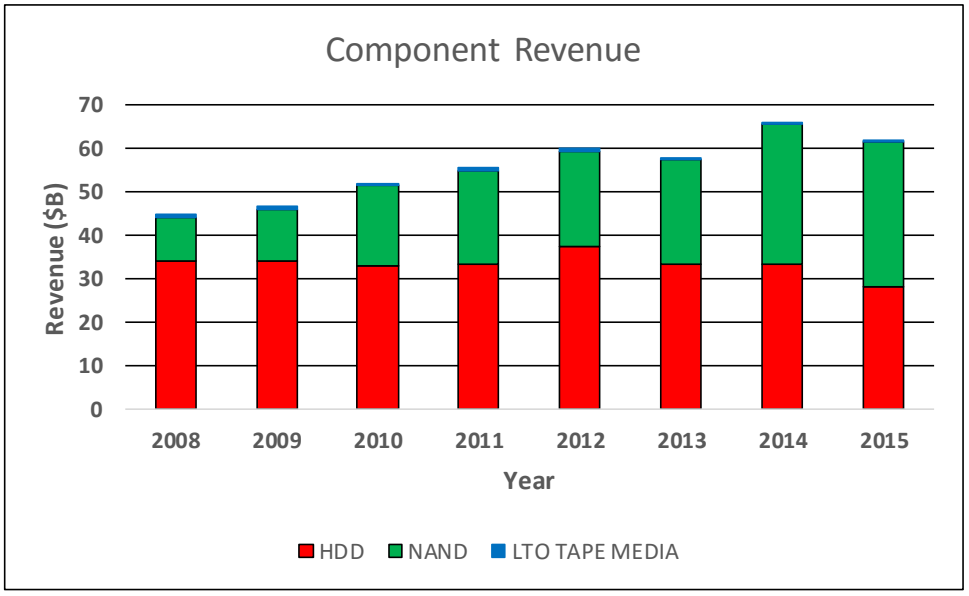


Two Contrarian Trends from 2015 Data

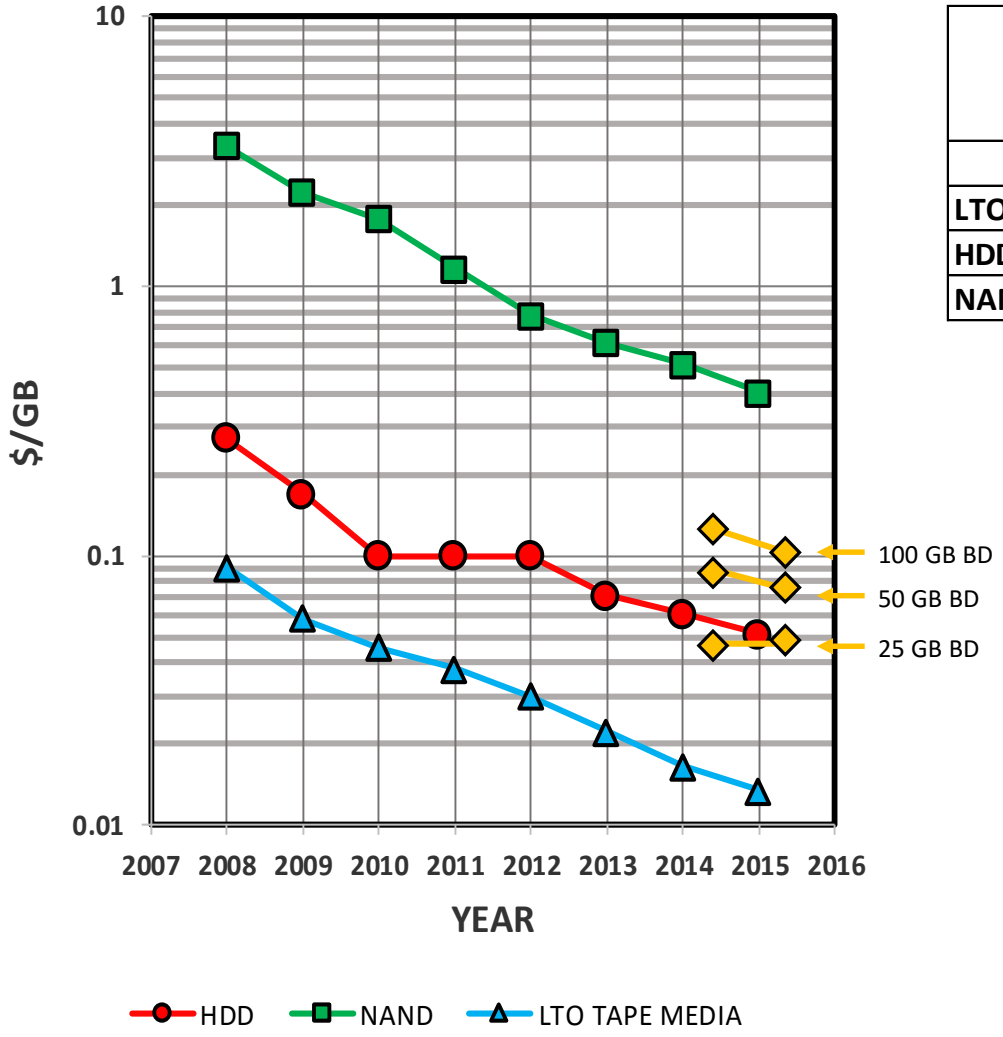
- Total annual manufactured Exabytes shows a linear trend (i.e. not exponential) with an annual increase over the last 8 years of 77 EB / YR ($r^2 = 0.98$)



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



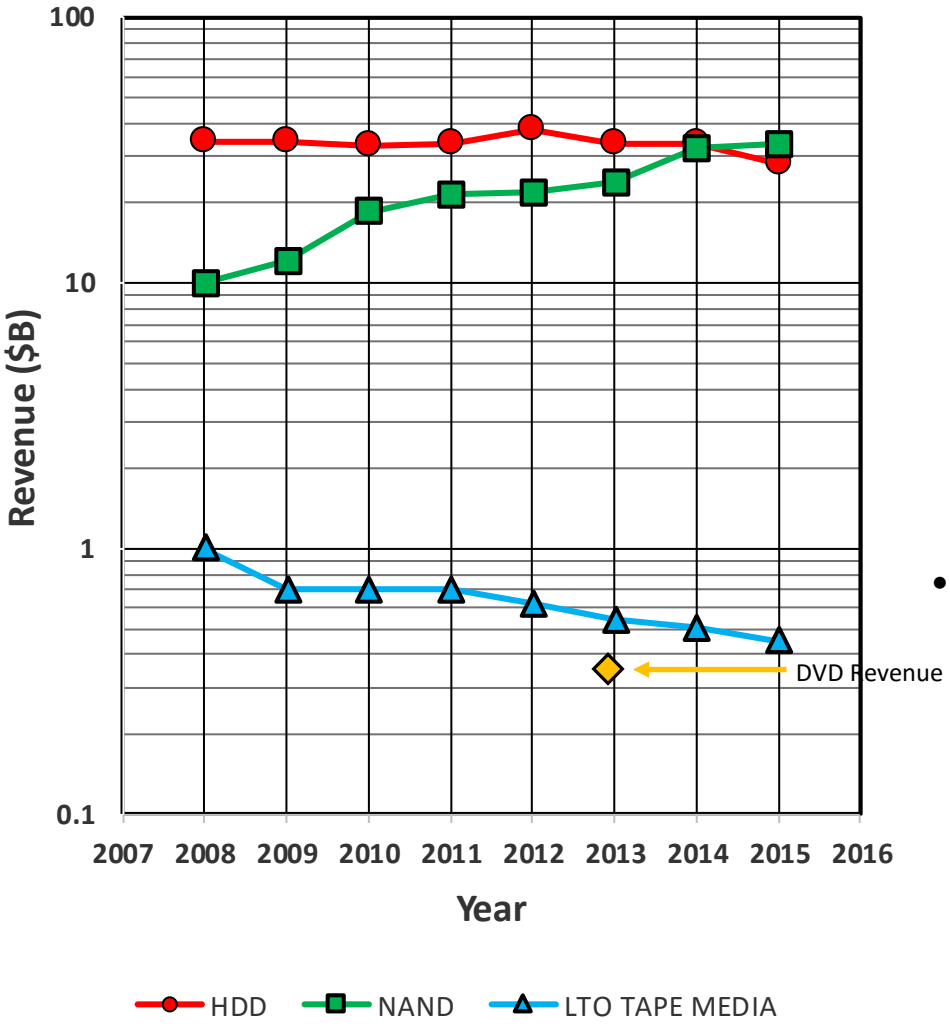
$/GB Trends: 2008-2015



$/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.

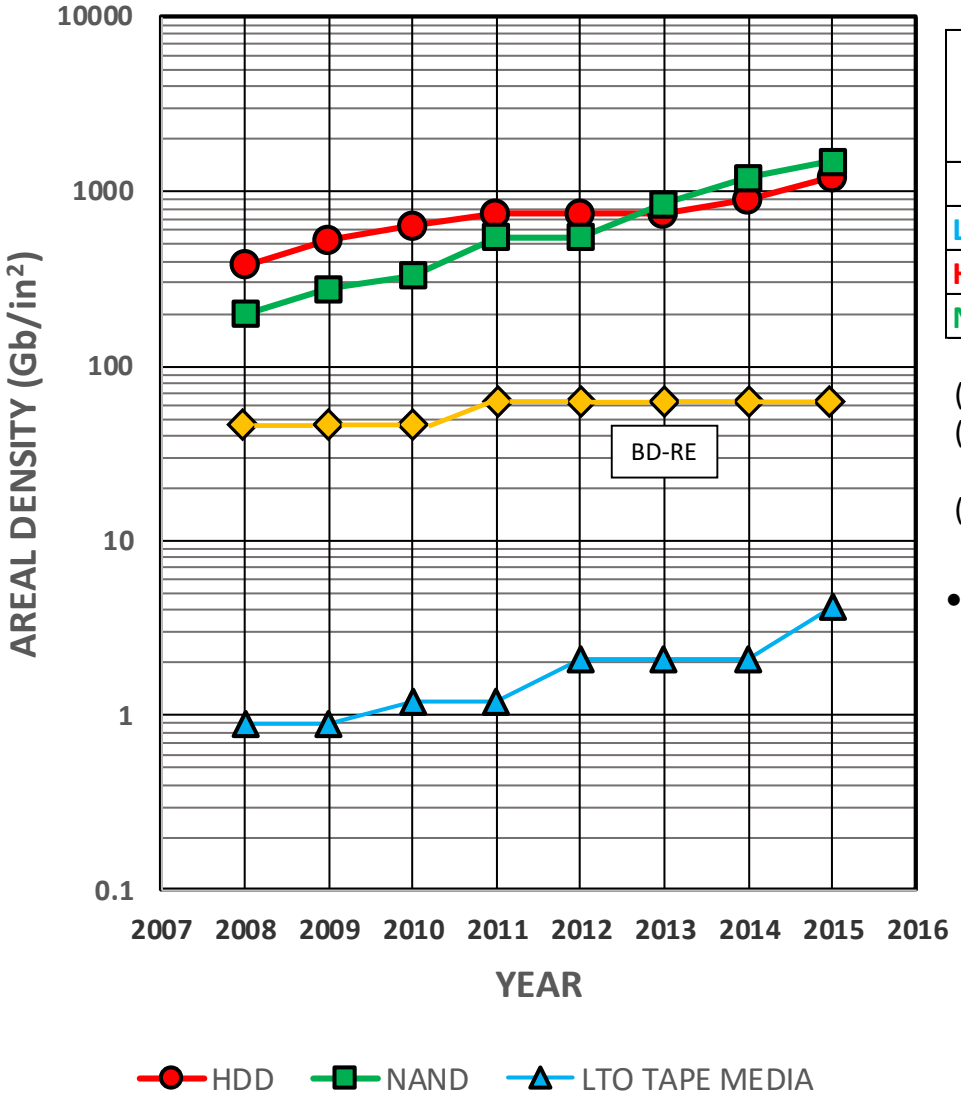
Revenue Trends: 2008-2015



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

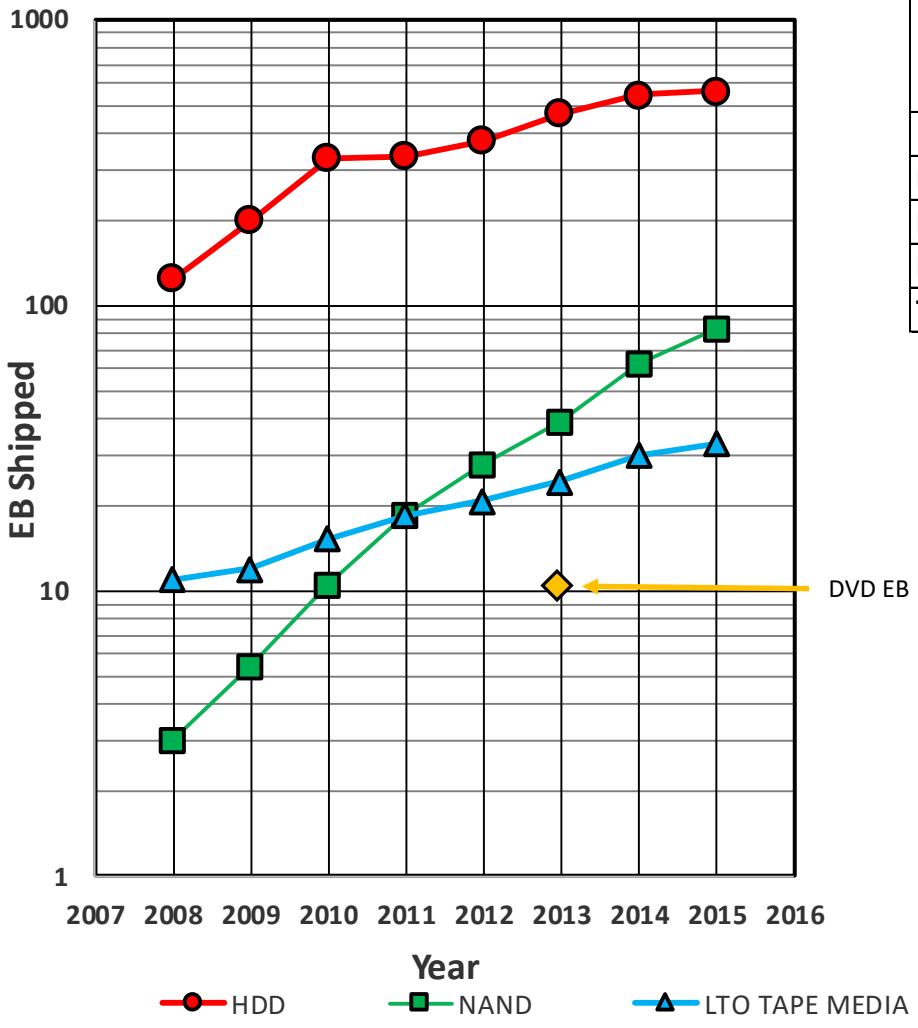


AREAL DENSITY (Gb/in²)	2014	2015	1 YEAR % Δ	7 YEAR ANNUAL % Δ	
LTO TAPE MEDIA	2.1	4.3	104.8%	25.0%	(1)
HDD	900	1000	11.1%	14.8%	(2)
NAND	1200	1500	25.0%	33.4%	(3)

(1) LTO7 introduced YE2015
(2) HDD density increase represents shingle magnetic recording – 800 Gb/in^2 for 3.5" HDD and 1000 Gb/in^2 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/in^2 range.
  - NAND areal density difficult to determine since the classic 4F^2 cell design is not rigorously used.

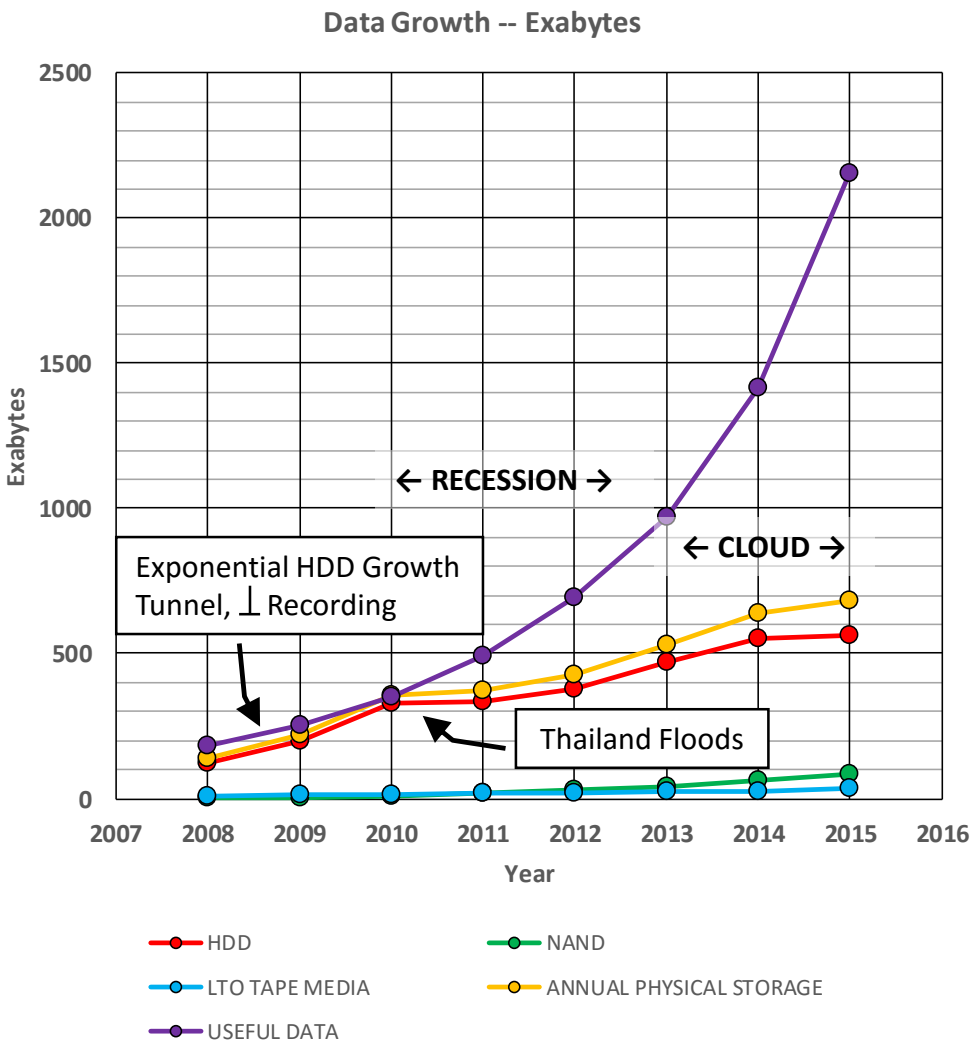
Exabyte Shipment Trends: 2008-2015



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 …)**