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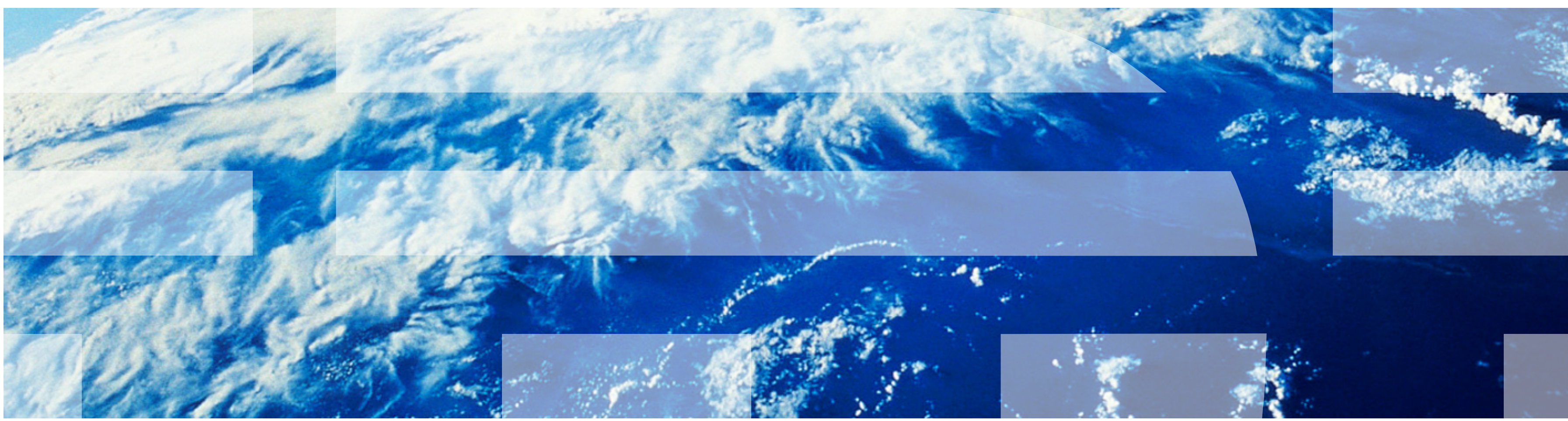
VOLUMETRIC DENSITY TRENDS (TB/in³) TAPE, HDD, NAND FLASH, Blu-Ray



Overview

- Topics
  - Develop a methodology to forecast 5 and 10 year capacity trends in storage components, i.e. HDD, SSD, TAPE Cartridge, Optical Blu-ray Disk (BD) Cartridge by using the last 6 years of areal density growth history
  - Introduce the concept of volumetric density (TB/in^3) or component storage capacity in a fixed volume
  - Describe volumetric strategies and limitations for HDD, SSD, TAPE, BD
  - Present Forecasts

- Key Points
  - Areal density growth in memory technologies is no longer 40% per year, i.e. a doubling every two years
  - Some volumetric strategies add more physical media into the component, i.e. more disks per HDD, more tape length per cartridge, double sided BD disks, and are **one time** strategies and not sustainable as a "Moore's Law" metric
  - Other volumetric strategies add more physical media onto a substrate, i.e. 3D cell design for NAND, multiple layers of smaller bit cells for BD, and are potentially sustainable as a "Moore's Law" metric
  - The only strategy for HDD to increase **areal** density is to "develop" against the realities of nano-technology. Other storage technologies have options for density growth not constrained by length scale limits.

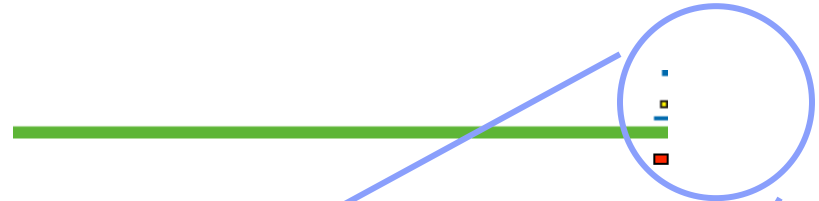
Storage Statistics 2008-2013 (what we presented to LOC in 2013)

	YE 2008	YE2009	YE2010	YE2011	YE2012[1]	YE2013[2]
HDD						
Units (HDDs millions)	540	557	652	620	577	551
PB Shipped (PB)	125000	200000	330000	335000	380000	470000
Areal Density (Gb/in²)	380	530	635	750	750	750(900)
Revenue ($ billions)	34.0	34.0	33.0	33.5	37.5	33.4
$/GB Shipped	0.272	0.170	0.100	0.100	0.100	0.071
NAND						
Units (2GBs millions)	1500	2715	5232	9326	14000	19500
PB Shipped (PB)	3000	5430	10464	18600	28000	39000
Areal Density (Gb/in²)	200	280	330	550	550	850
Revenue ($ billions)	10.0	12.1	18.5	21.5	22.0	24.0
$/GB Shipped	3.33	2.23	1.77	1.16	0.78	0.615
LTO TAPE						
Units (Cart. millions)	20	24	25	25	22.7	20.4
PB Shipped (PB)	10400	12165	15300	17800	19500	22500
Areal Density (Gb/in²)	0.9	0.9	1.2	1.2	1.2(2.1)	2.1
Revenue ($ billions)	1.0	0.7	0.7	0.7	0.62	0.54
$/GB Shipped	0.093	0.061	0.046	0.038	0.032	0.024

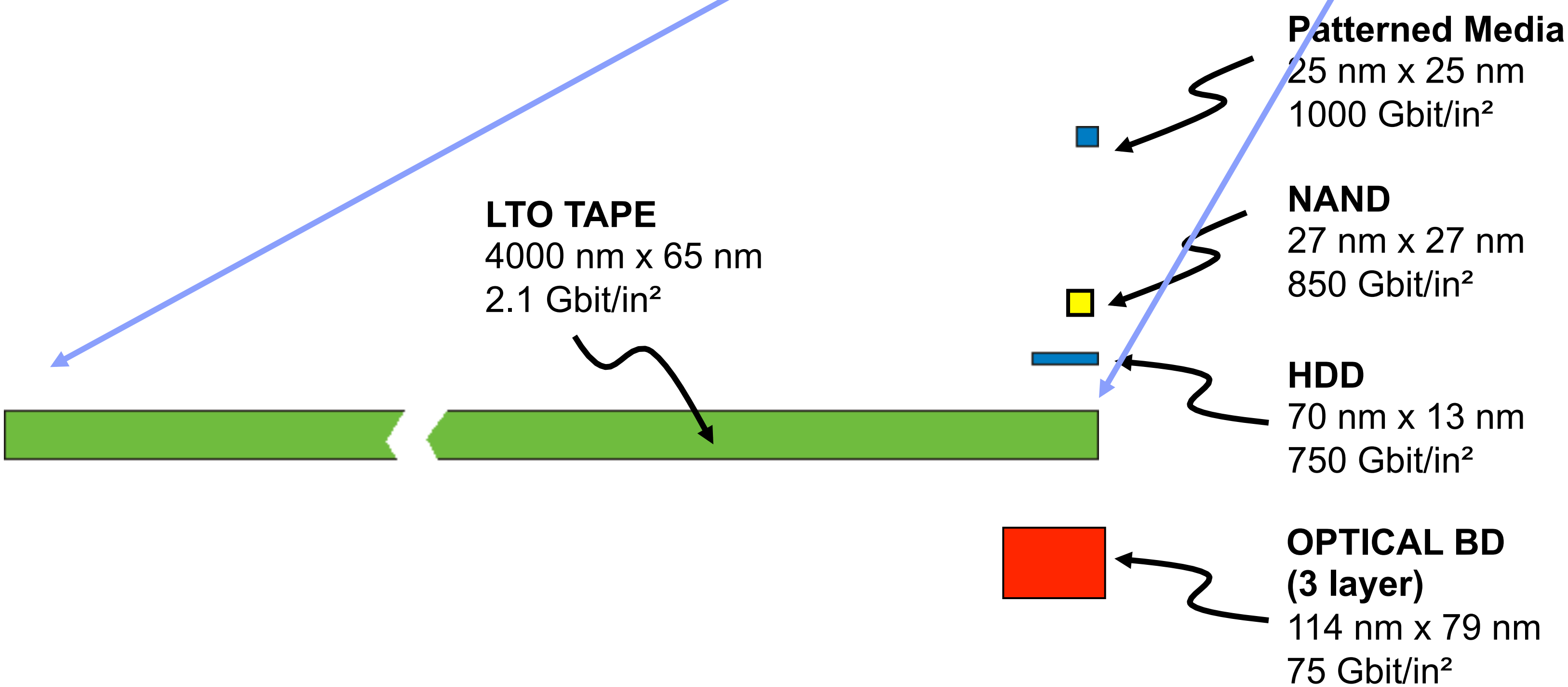
1. LTO6 introduced 12/2012
2. HDD likely using shingling with 20% density uplift

Storage Landscape (what we presented to LOC in 2012)

- Scaled Bit Cells



- Magnified View of Scaled Bit Cells



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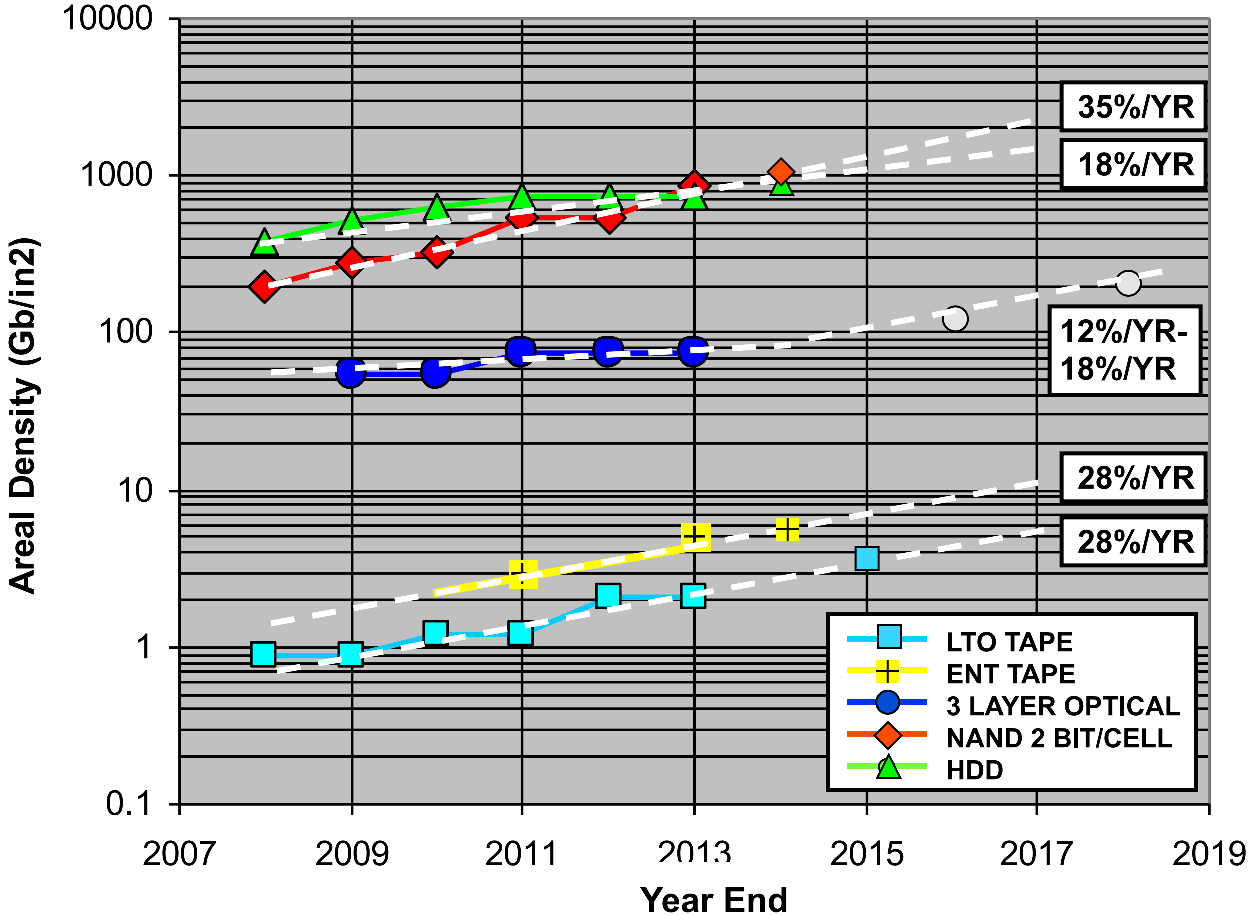
The Volumetric Storage Density Environment – YE 2013

- Today's Components: 3.5" HDD, 2.5" SSD, LTO and ENT cartridges, 12 disk BD cartridge
- Question: What future storage component capacities can be anticipated in the 5 and 10 year time frame
- Component Capacities now range from 1 TB to 5 TB – 5X
- Volumetric densities range from 0.33 TB/in³ to 0.06 TB/in³ -- 5X
- Areal Densities range from 2.1 Gb/in² to 900 Gbit/in² -- 450X

	NAND SSD	HDD	LTO TAPE	ENT TAPE	OPTICAL BD
Component	2.5" drive	3.5" drive	LTO cartridge	Enterprise cartridge	12 disk cartridge
Volume	3.0 in³	23.7 in³	20.4 in³	20.4 in³	21.3 in³
Volumetric Strategy	2 bits/cell	5 platters	840 m tape	840 m tape	3 layer disk
Areal Density	900 Gbit/in²	860 Gbit/in²	2.1 Gbit/in²	3.1 Gbit/in²	75 Gbit/in²
Capacity	1 TB	5 TB	2.5 TB	4 TB	1.2 TB
Storage Density	0.33 TB/in³	0.21 TB/in³	0.12 TB/in³	0.20 TB/in³	0.06 TB/in³

Historical Areal Densities

- 6 year history of areal density growth – **a measure of technical vitality for a technology**
  - – NAND bit density now greater than HDD bit density
  - – Blu-ray (BD) has proposed an aggressive roadmap
  - – HDD has at best an 18%/YR areal density growth over the last 6 years



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Areal Density and Length Scales

- Extending areal density growth rates to the future leads to length scale (e.g. nano technology) challenges

	AD Increase (2008-20013)	5 Year AD Increase (2019)	10 Year AD Increase (2014)
LTO TAPE	28%/yr	3.4X	11.8X
ENT TAPE	28%/yr	3.4X	11.8X
OPTICAL BD	12%/yr (18%/yr)	2.3X	5.2X
NAND	35%/yr	4.5X	20.1X
HDD	18%/yr	2.3X	5.2X

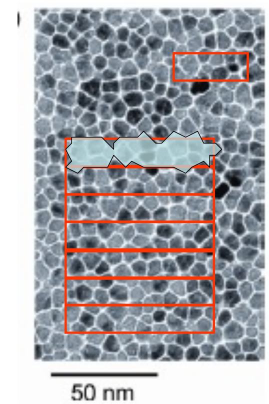
	2014 Bit Cell	2019 Bit Cell	2024 Bit Cell
LTO TAPE	4000 nm x 65 nm	1400 nm x 55 nm	600 nm x 50 nm
ENT TAPE	2500 nm x 65 nm	840 nm x 55 nm	360 nm x 50 nm
OPTICAL BD	320 nm x 80 nm	225 nm x 50 nm	225 nm x 22 nm
NAND	22 nm x 22 nm	10 nm x 10 nm	5 nm x 5 nm
HDD	70 nm x 13 nm	40 nm x 10 nm	25 nm x 7 nm

- Areal density deficiencies can be compensated for with volumetric strategies

Volumetric Strategies

- Definition: Storage media consists of an active memory layer supported on a substrate
- Option 1 (substrates): More storage media into fixed volume of the component (component capacity increases while areal density remains constant)
  - Increase platter number in an HDD by reducing disk to disk spacing with thinner disks and sliders (5 ➔ 8)
  - Increase tape length in a cartridge by reducing substrate thickness (840 m ➔ 1140 m
  - Increase disk number in an archival optical cartridge by thinning disks
  - Strategy not sustainable, i.e. **one time or two time** impacts that can at most increase capacity by ~ 1.4X
- Option 2 (layers): More active memory layers on a substrate
  - Example 1: 3D NAND cell designs with 20+ layers
  - Example 2: BD disks with 3 layers of phase change material
  - Example 3: BD disks with layers on the top and bottom surfaces of the disk
  - Strategy attributes
    - Effective areal density per substrate surface scales with the number of layers, N
    - Nano technology or length scale limits can be circumvented by using larger feature sizes compensated by more physical layers N
- Issue: Cost to "integrate" more active layers on a substrate vs cost of "adding" more substrates

- Areal density strategy: move to smaller bit cells and address nano-technology physics but:
  - Grain size vs bit cell size requires grain size distribution control
  - Sensor size tracks bit width
  - HAMR technology changes multiple elements of the head/disk environment which must be cost effectively manufactured with **reliable** performance and which must be **scalable** for several generations
    - New thermal write element
    - New finer grain media
    - New disk overcoat (thermal stress)
    - New head overcoat (thermal stress)
  - Shingle writing is a "one time" increase in density (removes guard band)



- Volumetric strategy: add more platters to the drive
  - 5 platters in 2013, 6 platters in 2014, 8 platters in 2016???
  - Mechanical constraints of HDD form factor
  - Thinner disk and thinner head sliders lead to new dynamic effects
  - Potential for one time component capacity increases ~ 30%

- Reality – HAMR is difficult
  - Reducing bit cell size by 55% in 5 years is aggressive.

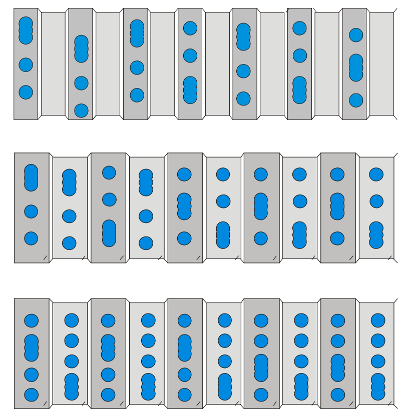
TAPE Volumetrics

- Areal density strategy: move to smaller bit cell sizes using already proven transducer technology existing in the HDD industry. Bit cell dimensions in the next 10 year period do not approach the length scales of today's HDD, NAND, and Optical features but:
  – Media grain size must scale as bit cell decreases
  – Logical requirement will be a transition from particulate media to sputtered media as practiced by HDD
  – Development cost

- Volumetric strategy: add more tape length
  – LTO and Enterprise cartridge tape lengths ~ 840 m
  – Some Enterprise cartridge tape lengths ~ 1140 m (+35%)
  – One time increase from thinning tape substrate from 5.5 um to 4.0 um

- Reality: TAPE likely maintains 28% annual density growth rate
  – LTO transitions to larger tape length
  – Smaller particle media for higher densities requires development investment

- Areal density strategy: continue to reduce bit cell size while being constrained by optical source λ (405 nm), optics NA (0.85), and laser half power spot size (480 nm) – nano optics limits
  - New archival areal density roadmap announced in March, 2014 with **no** time lines
  - Land and groove recording (1.4X)
  - Signal processing (1.7X)
  - 2 bit/cell with 4 different reflectivities (>7 years out)



Traditional BD
--0.32 um groove pitch
--3 layer, 75 Gbit/in²

Valley and Plateau BD
--0.45 um groove pitch
--3 layer, 118 Gbit/in²

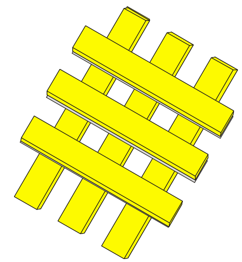
Valley and Plateau BD
--Signal processing
--0.45 um groove pitch
--3 layer, 189 Gbit/in²

- Volumetric strategy:
  - BD already using volumetrics at the substrate level, i.e. using 3 layers of phase change material, each separated by 25 um; to store information
  - Double sided disks (2X) but cost might be cost neutral ($/GB) if two substrates glued together – one time enhancement

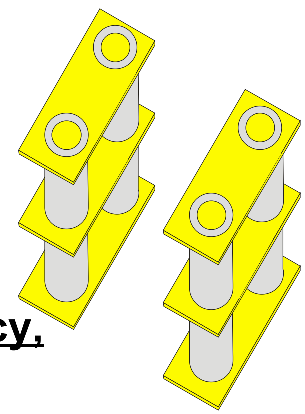
- Reality– potential but unproven path to increase areal density 2.5X
  - Present BD 3 layer disk capacity is 100 GB!!!
  - Unknowns are **timing** and development requirement and manufacturing capacity
  - 2 bit per cell is unlikely, greater than 3 layers is challenging
  - Constraints to 405 nm source limits density approaches

NAND Volumetrics

- Areal density strategy is to pursue classical scaling from the present 16 nm node to the 13 nm node with nano issues of lithography, nearest cell interactions, and charge limitations
  and
  3D cell designs with multiple layers (> 20) and larger cell area
  – 20 layer 3D designs at 40 nm node equivalent to traditional 2 bit/cell design at 16 nm
  – Processing intensive strategy with is the core strength of the IC industry



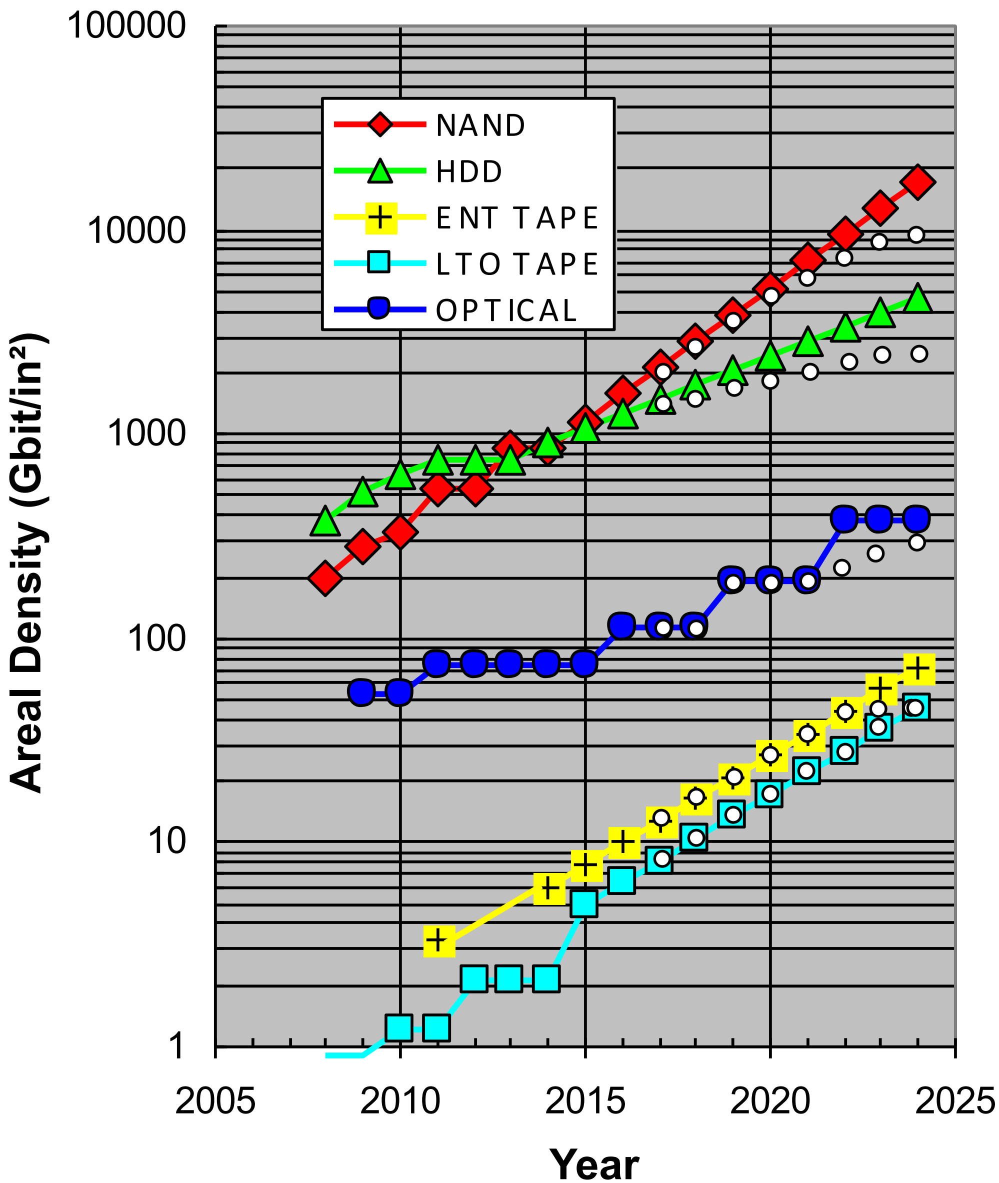
2D cell
-- $4F^2$, F = 16 nm
-- 2 bits/cell
-- 512 nm^2 / bit



3D cell
-- $6F^2$, F = 40 nm
-- 1 bits/cell
-- 9600 nm^2 / bit
-- 20 layers
-- 480 nm^2 / bit
(effective area)

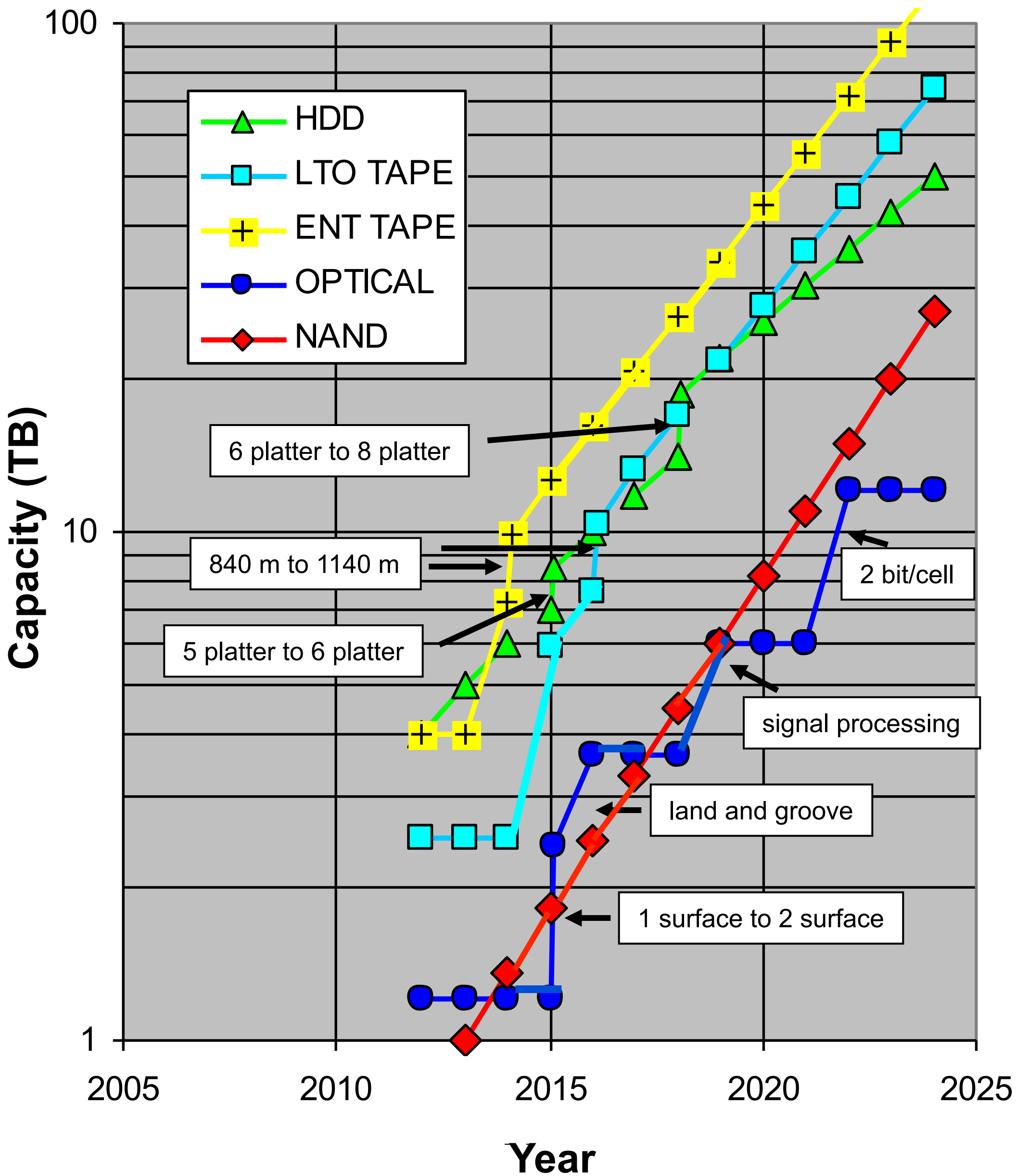
- Volumetric strategy
  – 3D design is the classical volumetric design to exploit the thickness dimension in silicon wafer processing
  – **The strategy addresses nano technology issues in a rational manner, solving lithography, charge deficiency, and nearest neighbor interactions**

- Reality:
  – Density growth comes from doubling layers in the 3D device every 2 years with 2 cycles being 80 layers (4X) and going to 2 bits/cell adds an additional 2X
  – Processing assumes simultaneous processing of all layers but process reality may dictate processing fewer layers simultaneously – cost and yield



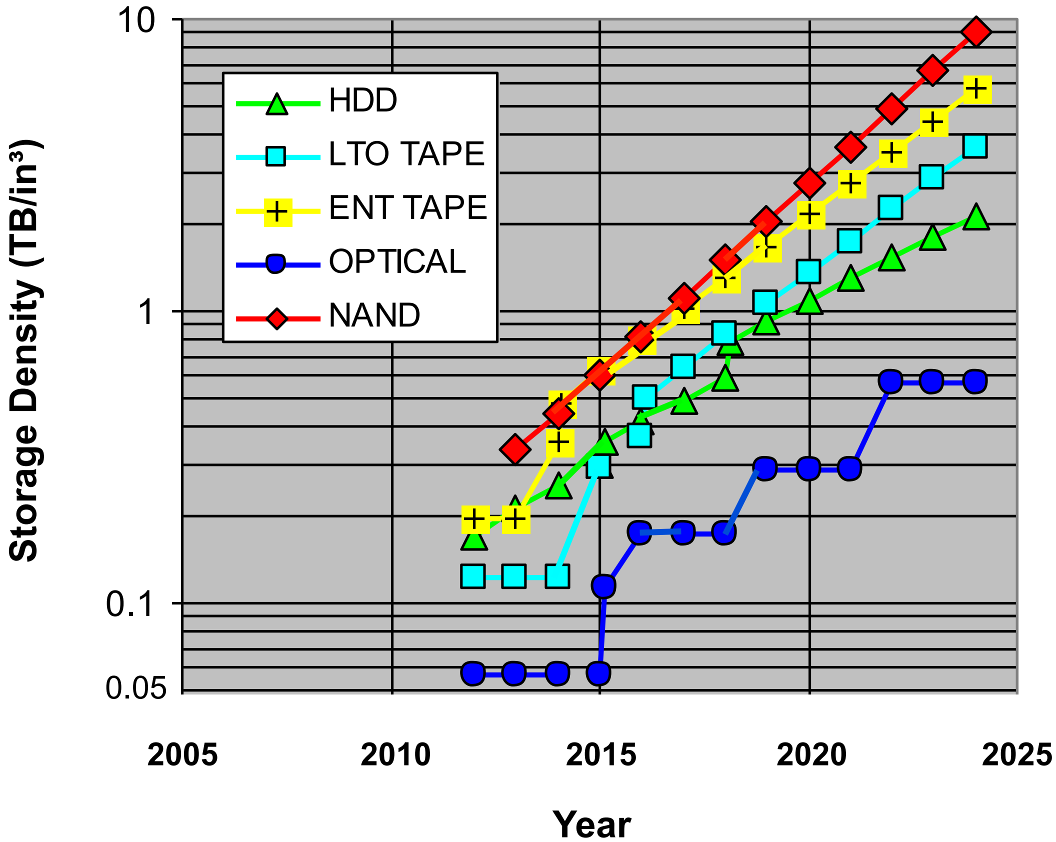
- > 250X spread in areal densities
- TAPE -- media issues
- HDD -- HAMR, sensors, media, reliable components, nano limitations remain
- Optical -- unproven roadmap history, continuation with same optical source
- NAND: processing implementation of 3D design but strategy addresses nano limitations

Component Capacity vs Time (best case)



- Component capacity scaled from 2013 data using best case areal density growths from 6 year history
- 5X spread in capacity
- HDD – convergence with TAPE
- OPTICAL – significant capacity lag relative to TAPE and HDD

Volumetric Density (TB/in³) for best case scenarios



- Superior volumetric characteristics of NAND (no moving parts)
- LTO and ENT TAPE essentially time shifted by 2 to 3 years
- 10X spread in TB/in³
- OPTICAL – significant lag relative to all technologies
- TAPE – competitive with HDD

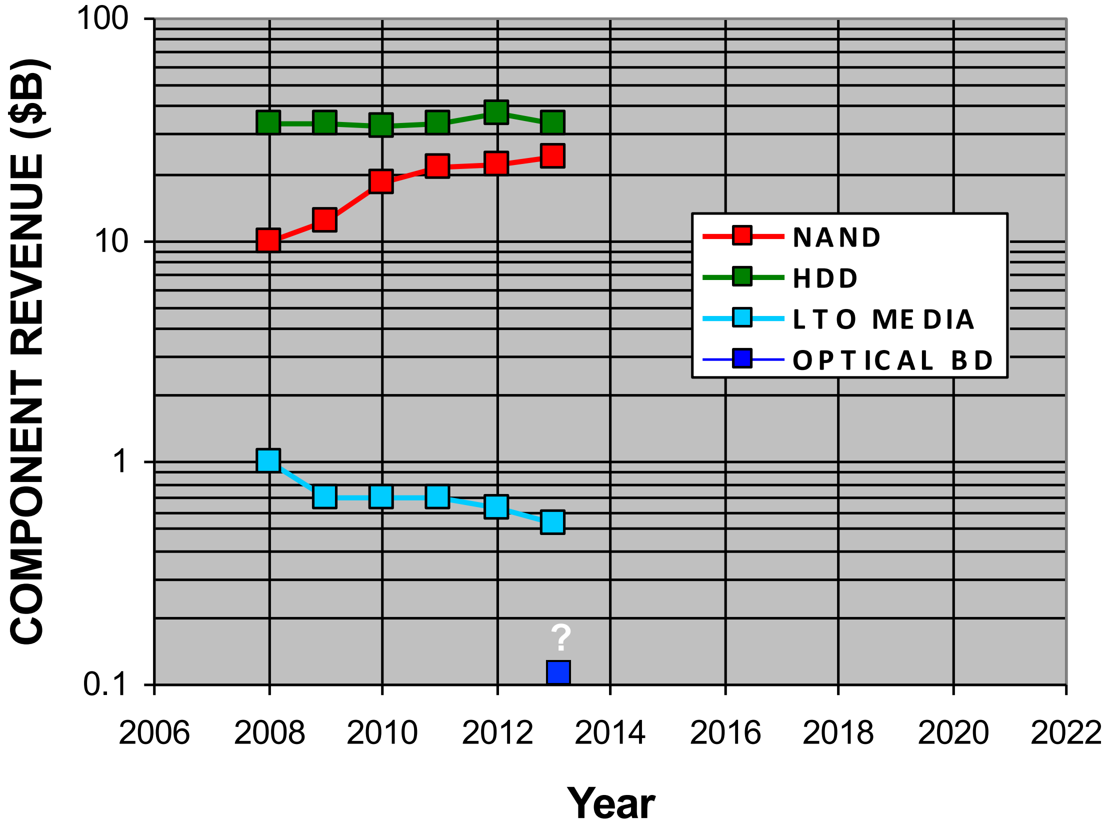
Summary

- For TAPE, HDD, NAND Flash, and OPTICAL BD the areal density growth rates are slowing. Perceived 40% annual growth rates are not being achieved
- Future component capacity growth will be achieved by a combination of areal density increases and "one time" or "two time" volumetric enhancements
- NAND density strategies have the advantage of directly addressing nano technology issues
- Optical density strategies have the disadvantage of being constrained to one wavelength source
- HDD must address, continually, nano length scale issues of media grains, sensor size and must demonstrate new technologies with manufacturable and reliable components
- TAPE lags the areal density of the other technologies by a factor of > 100X. Nano technology impacts media needs but component needs are already practiced by HDD.
- Critical Issue (not the scope of this talk)
  - $/GB trends of 25%/yr reductions will likely not continue
  - Development costs
  - Manufacturing tooling
  - From Richard Feynman's 1959 lecture we know that "There is plenty of room at the bottom" (i.e. smaller length scale devices) but now, 55 years later, "the bottom" requires more and more capital commitment

BACKUP

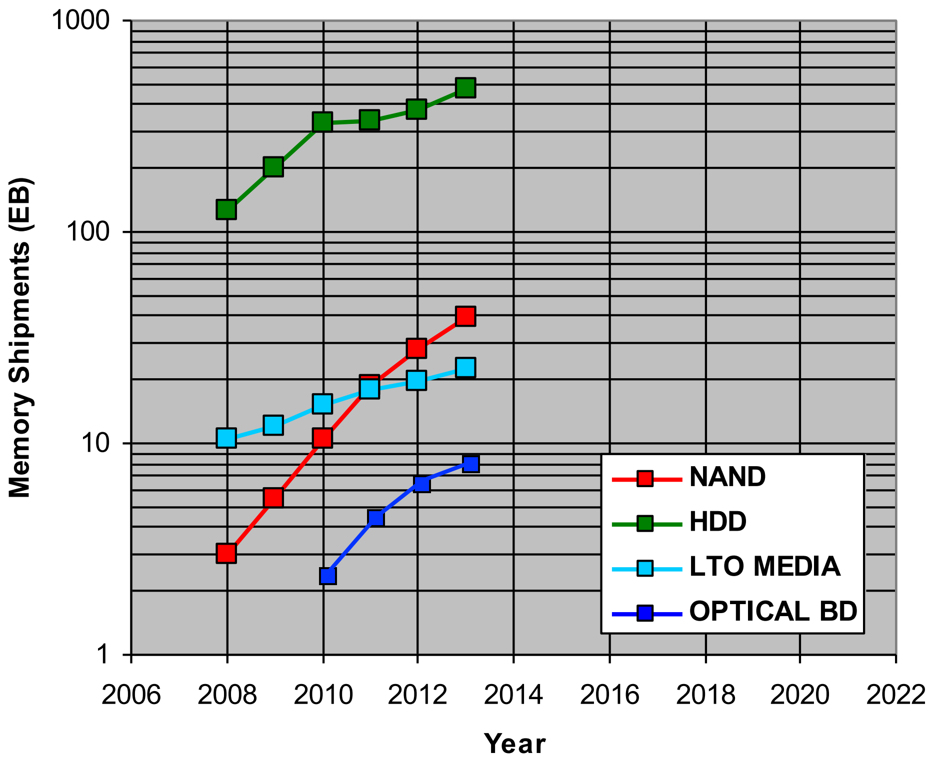
Component Revenue

- HDD revenue is stable (decrease in 2013 reflects Thailand floods)
- NAND revenue increasing but slowed in 2013
- LTO media revenue is decreasing
- No data on Optical BD revenue.



Exabyte (EB) Shipments and NAND Replacing HDD

- HDD shipped 480 EB in 2013 with $33B in revenue
- IDC shows that Enterprise and Capacity Optimized (CO) HDDs accounted for $5B in revenue
- An average cost of $0.05/GB implies 100 EB for Enterprise and CO drives
- EBs associated with HDD Enterprise and CO drives is 2.5X greater than all NAND produced in 2013



- NAND manufacturing metrics
  - 12” wafer at 16 nm node contains 6.4TB of NAND memory
  - A $3.5B NAND factory processes 1000 wafers per day
  - A $3.5B NAND factory produces 2.46 EB annually
  - Producing an additional 100 EB of NAND would require an additional 40 NAND factories with a capital investment of > $125B