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 Verifiable

- Topics
  - Storage Landscape for 2008-2015
  - Moore’s Law – Underachieving implies components are more valuable
  - Exabytes and Millions of Square Inches and Areal Density
  - MSI Examples and Specific Trends
  - Summary and the Future
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:

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

*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 - TLC**
    - 1500 Gbit/in²
    - 19nm x 19nm
  
  - **NAND - MLC**
    - 1100 Gbit/in²
    - 24nm x 24nm
  
  - **NAND – TLC 3D**
    - 1500 Gbit/in²
    - 84nm x 84nm
    - 20 layers
  
  - **HDD**
    - 1000 Gbit/in²
    - 58nm x 11nm

- **TAPE**
  - 7 Gbit/in²
  - 2000nm x 47nm

- **Blu-Ray BD-XL**
  - 75 Gbit/in²
  - 180nm x 180nm
  - 3 layers

- **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

<table>
<thead>
<tr>
<th></th>
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<td><strong>HDD</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Units (HDD millions)</td>
<td>540</td>
<td>557</td>
<td>652</td>
<td>620</td>
<td>577</td>
<td>551</td>
<td>564</td>
<td>470</td>
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<td>PB Shipped (PB)</td>
<td>125000</td>
<td>200000</td>
<td>330000</td>
<td>335000</td>
<td>380000</td>
<td>470000</td>
<td>549000</td>
<td>565000</td>
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<td>Areal Density (Gb/in²)</td>
<td>380</td>
<td>530</td>
<td>635</td>
<td>750</td>
<td>750</td>
<td>900</td>
<td>900</td>
<td>1000¹</td>
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<td>Revenue ($ billions)</td>
<td>34.0</td>
<td>34.0</td>
<td>33.0</td>
<td>33.5</td>
<td>37.5</td>
<td>33.4</td>
<td>33.4</td>
<td>28.3</td>
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<td>$/GB Shipped</td>
<td>0.272</td>
<td>0.170</td>
<td>0.100</td>
<td>0.100</td>
<td>0.100</td>
<td>0.071</td>
<td>0.061</td>
<td>0.051</td>
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<td><strong>NAND</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Wafers (12” -- millions)</td>
<td>7.3</td>
<td>8.3</td>
<td>9.7</td>
<td>11.3</td>
<td>12.1</td>
<td>13.7</td>
<td>14.8</td>
<td>15.9</td>
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<tr>
<td>PB Shipped (PB)</td>
<td>3000</td>
<td>5430</td>
<td>10464</td>
<td>18600</td>
<td>28000</td>
<td>39000</td>
<td>62500</td>
<td>83000</td>
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<tr>
<td>Areal Density (Gb/in²)</td>
<td>200</td>
<td>280</td>
<td>330</td>
<td>550</td>
<td>550</td>
<td>850</td>
<td>1200</td>
<td>1500</td>
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<tr>
<td>Revenue ($ billions)</td>
<td>10.1</td>
<td>12.1</td>
<td>18.5</td>
<td>21.5</td>
<td>22.0</td>
<td>24.0</td>
<td>32.2</td>
<td>33.2</td>
</tr>
<tr>
<td>$/GB Shipped</td>
<td>3.33</td>
<td>2.23</td>
<td>1.77</td>
<td>1.16</td>
<td>0.78</td>
<td>0.615</td>
<td>0.515</td>
<td>0.401</td>
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<tr>
<td><strong>LTO TAPE MEDIA</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Units (Cart millions) ¹</td>
<td>27.1</td>
<td>24.3</td>
<td>25.0</td>
<td>24.3</td>
<td>23.4</td>
<td>21.6</td>
<td>22.2</td>
<td>19.4</td>
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<tr>
<td>PB Shipped (PB) ¹</td>
<td>11050</td>
<td>11960</td>
<td>15340</td>
<td>18420</td>
<td>20680</td>
<td>24270</td>
<td>30100</td>
<td>33020</td>
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<tr>
<td>Areal Density (Gb/in²)</td>
<td>0.9</td>
<td>0.9</td>
<td>1.2</td>
<td>1.2</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>4.1</td>
</tr>
<tr>
<td>Revenue ($ billions) ²</td>
<td>1.0</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.62</td>
<td>0.54</td>
<td>0.50</td>
<td>0.45</td>
</tr>
<tr>
<td>$/GB Shipped</td>
<td>0.0905</td>
<td>0.0585</td>
<td>0.0456</td>
<td>0.0380</td>
<td>0.0300</td>
<td>0.0222</td>
<td>0.0166</td>
<td>0.0134</td>
</tr>
</tbody>
</table>

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¹ 2.5” HDD areal density -- 1000 Gbit/in², 3.5” HDD areal density -- 800 Gbit/in²  
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
- HDD; 565,000 PB; 83%
- NAND; 83,000 PB; 12%
- LTO TAPE; 33,000 PB; 5%

2012 PB Shipments – 429,000 PB
- HDD; 380,000 PB; 89%
- NAND; 28,000 PB; 6%
- LTO TAPE; 21,000 PB; 5%
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**
  - \( \$/GB \text{ decreases } 30\% \text{ per year or } 50\% \text{ every two years} \)
  - \( \text{AD increases } 40\% \text{ per year or } 100\% \text{ every two years} \)
  - \( \text{NET} = \) 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 \( \sim 20\% / yr \) for the three year period 2013 – 2015
  - Areal Density \( \sim 40\% / yr \) 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

<table>
<thead>
<tr>
<th></th>
<th>4 TB Drive</th>
<th>10 PB System</th>
</tr>
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<tbody>
<tr>
<td>2016 Cost</td>
<td>$160</td>
<td>$400K</td>
</tr>
<tr>
<td>2020 Cost (20%/yr $/GB Decrease)</td>
<td>$65</td>
<td>$162K</td>
</tr>
<tr>
<td>2020 Cost (30%/yr $/GB Decrease)</td>
<td>$40 (Moore’s Law)</td>
<td>$100K (Moore’s Law)</td>
</tr>
</tbody>
</table>

- 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

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

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 duopolies or triopolies
- 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

<table>
<thead>
<tr>
<th></th>
<th>$/GB</th>
<th>2014</th>
<th>2015</th>
<th>1 YEAR % Δ</th>
<th>8 YEAR ANNUAL % Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTO TAPE MEDIA</td>
<td>0.0166</td>
<td>0.0134</td>
<td>-19.3%</td>
<td>-23.9%</td>
<td></td>
</tr>
<tr>
<td>HDD</td>
<td>0.061</td>
<td>0.051</td>
<td>-16.4%</td>
<td>-21.3%</td>
<td></td>
</tr>
<tr>
<td>NAND</td>
<td>0.515</td>
<td>0.401</td>
<td>-22.1%</td>
<td>-26.1%</td>
<td></td>
</tr>
</tbody>
</table>

- **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

<table>
<thead>
<tr>
<th></th>
<th>2014</th>
<th>2015</th>
<th>1 YEAR % Δ</th>
<th>8 YEAR ANNUAL % Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTO TAPE MEDIA</td>
<td>0.5</td>
<td>0.45</td>
<td>-10.0%</td>
<td>-8.4%</td>
</tr>
<tr>
<td>HDD</td>
<td>33.4</td>
<td>28.3</td>
<td>-15.3%</td>
<td>-2.6%</td>
</tr>
<tr>
<td>NAND</td>
<td>32.2</td>
<td>33.2</td>
<td>3.1%</td>
<td>18.5%</td>
</tr>
<tr>
<td>TOTAL REVENUE</td>
<td>66.1</td>
<td>61.95</td>
<td>-6.3%</td>
<td>4.7%</td>
</tr>
</tbody>
</table>

• 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

<table>
<thead>
<tr>
<th></th>
<th>2014</th>
<th>2015</th>
<th>1 YEAR %Δ</th>
<th>7 YEAR ANNUAL %Δ</th>
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<td>LTO TAPE MEDIA</td>
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<td>14.8%</td>
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<tr>
<td>NAND</td>
<td>1200</td>
<td>1500</td>
<td>25.0%</td>
<td>33.4%</td>
</tr>
</tbody>
</table>

(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, 5F² 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 the 800 Gbit/in² range.
  • NAND areal density difficult to determine since the classic 4F² cell design is not rigorously used.
Exabyte Shipment Trends: 2008-2015

- 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

Figure of Merit (Revenue, Volume, ...)

Consolidation, high volume manufacturing

Post consumer driven design points

High growth, large investment, multiple players

Technology Companies Lead

New Technology, Low Volume, High Margin

Flash Consumer

Flash Enterprise

HDD

Tape

Mature Technology, Stable Market

Time

High Volume, Lower Margin, Consumer Commodity