Business of NAND: Trends, Forecasts & Challenges

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Key Messages

• Ramp of 3D NAND will be slower than most people think …
  • And uneven by vendor
  • NAND roadmaps likely will bi-furcate (3D NAND best aligns with SSD’s)

• 3D NAND cost reduction will be linear and **not** a step function
  • TLC will dominate in 3D NAND near term (the Question of QLC ramp)
  • Scaling (and complexity) in 3D NAND multiple ways: layers, x-y, stacking

• SSD/Storage architecture changes
  • Enterprise storage tiers are growing more sophisticated
  • What role will Hyperscale play in SSD (and thus NAND) roadmaps?
  • Client SSD tipping point: Runaway vs. Plateau
Agenda

• Where is NAND today?

• What is NAND going?
  ➢ Segment level
  ➢ Component level

• What are the Challenges?
NAND: Status
NAND Consumption (Segment)

- **Handsets**: CAGR: 3%
- **Solid State Drives**: CAGR: 55%
- **Portable Media Players**: ~85%
- **Tablets**: Other
- **USB Drives**: Other
- **Digital Cameras**: Other

NAND usage by segment (% of bits)

NAND usage by segment (% of bits) 2011 vs 2015

Flash Memory Summit 2016
Santa Clara, CA
NAND Suppliers (Vendors)

2012 NAND MSS (bits)
- Samsung: 31%
- Toshiba: 10%
- SanDisk: 20%
- Micron: 11%
- SK Hynix: 14%
- Intel: 11%

2015 NAND MSS (bits)
- Samsung: 31%
- Toshiba: 8%
- SanDisk: 14%
- Micron: 15%
- SK Hynix: 11%
- Intel: 21%
SSD Unit Shipments

Enterprise CAGR: 32%
Client CAGR: 21%

Enterprise 50% of Revenue & 30% of Bits (and growing)

Source: Source: IDC, Gartner, I.H.S, Trendfocus, Trendforce and Internal 2016
SSD Revenue Market Share

- $17B Market
- Samsung is leading
- Unit and Revenue leaders can be different
- Some SSD’s are unbranded

Source: IDC, Gartner, I.H.S, Trendfocus, Trendforce and Internal 1H 2016
Enterprise/Datacenter Revenue Share

- $8B+ Market
- Share varies widely between analysts
  - Definition of enterprise
  - Intel revenue reports
- Will change again with Sandisk merger

Source: IDC, Gartner, IHS, Trendfocus, Trendforce and Internal 1H 2016
Hyperscale … the hidden numbers

- Often Hyperscale internal use is hard to track easily
- DRAM can be argued to be a bellwether for SSD trends
  - Over 50% of DRAM enterprise bits ‘Cloud’ by 2017
- For more complex SSD’s:
  - What % will be direct vs. thru vendors optimizations?
  - How expansive will the BYO trend with tier 1 cloud vendors?
3D NAND: Component Trends
TLC Industry Output

TLC output secularly rising across Vendors
(with QLC products on the horizon)
2D to 3D NAND Volume Ramp

3D Volume Ramp Factors

- Technology readiness (3D TLC spec equivalent to 2D MLC)
- Economics of the last 2D NAND node
- Manufacturability & Yield
- Equipment planned
Markers to be monitored (next 12 months):

1. Product sampling and announcements in 2017
2. Technical complexity → specs/schedule from vendors

Question of QLC .... Two camps

3D TLC = 2D MLC

→ Hence – 3D QLC replace 2D TLC ... (of course)

3D scaling is multi dimensional (layer, x-y, stacking)

→ Hence – faster 3D TLC node introductions will be the focus
Is bi-furcation of NAND roadmaps inevitable? (or support for 2D nodes extended)

What about applications like...
1. Low cost Mobile
2. Low capacity client SSDs (for perf)
3. High performance low capacity

Enterprise SSD’s
Client SSD’s
High Capacity Mobile
HDD vs SSD Pricing

- SSD more expensive today (and tomorrow) per GB
- HDD cost improvement slow but still present
- SSD’s have power, reliability, performance advantages

*SSD’s unlikely to be cheaper in $/GB, but advantages will make it continue to make it grow vs. HDD*

Source: IDC, Trendforce, IHS
3D NAND: Segment Trends
Enterprise SSD’s

- PCIe driving innovative solutions
- Hyperscale has led initial charge with rising global deployments
- Mainstream PCIe closing gap with better performance & comparable economics to SATA
- PCIe & SAS will lead enterprise
Enterprise → New Storage Tiers

Key Metrics

<table>
<thead>
<tr>
<th></th>
<th>$/GB</th>
<th>Read/Write</th>
<th>Endurance</th>
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</thead>
<tbody>
<tr>
<td>DRAM</td>
<td>$3-5</td>
<td>7ns/7ns</td>
<td>1e18</td>
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<tr>
<td>Between DRAM &amp; NAND</td>
<td>100’s ns to low µs</td>
<td>Between DRAM &amp; NAND</td>
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<tr>
<td>Performance Optimized SSD (PCIe)</td>
<td>$0.4-1.0</td>
<td>100µs/25µs</td>
<td>100’s-10K PE cycles</td>
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<td>Capacity Optimized SSDs (SAS, SATA)</td>
<td>&lt; $0.4</td>
<td>0.5ms/50µs</td>
<td>100’s-10K PE cycles</td>
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<tr>
<td>Capacity Optimized HDDs</td>
<td>&lt; $0.05</td>
<td>2-10 ms</td>
<td>High</td>
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Flash Memory Summit 2016
Santa Clara, CA
Build-Your-Own: Economics

25-40% advantage

Controller
Board & Components
Manufacturing & Test
NAND (user GB)
Build-Your-Own: Platform Knobs

<table>
<thead>
<tr>
<th>Applications</th>
<th>Power Used</th>
<th>DRAM Density</th>
<th>Flash Density</th>
<th>Flash Type/Cost</th>
<th>Host I/F BW</th>
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<tbody>
<tr>
<td>Cold Storage</td>
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<tr>
<td>2.5” SSD (SAS/SATA)</td>
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<tr>
<td>Low/Mid PCIe SSD</td>
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<td>Medium</td>
<td>High</td>
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<tr>
<td>Enterprise PCIe SSD</td>
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<td>Medium</td>
<td>High</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Caching Adapter</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
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</tr>
</tbody>
</table>

**BYO motivation broader than cost arbitrage (Hyperscale with added qual advantages)**
Enterprise Controller Ecosystem

- **Complexity**
  - Multiple rev’s and related delays

- **Cost**
  - Several $10’s millions

- **Capability**
  - Specific technical expertise

- **Architectural maturity**
  - Multiple generations in production

*Microsemi (3rd party) Controller Customers*

- NAND Vendors
- SSD & AFA Vendors
- Hyperscale direct

*Flash Memory Summit 2016
Santa Clara, CA*
3D NAND: Forecasts
NAND Status: What is shipping?

- Micron has 128Gb 16nm Planar MLC at ~173mm$^2$ [0.74Gb/mm$^2$]
- Toshiba has 128Gb 15nm Planar TLC at ~100 mm$^2$ [1.28Gb/mm$^2$]
- Micron is shipping 32L 256Gb MLC/384Gb TLC at ~168mm$^2$ [1.5, 2.3Gb/mm$^2$]
- Toshiba has 128Gb 48L TLC Shipping
- Samsung is shipping 48L 256Gb TLC NAND 98mm$^2$ [2.6Gb/mm$^2$]
  - Continuing to ship 32L NAND as well
What is Announced or Expected

- Samsung will move to 64L 3D by end of year
- Micron published 768Gb TLC NAND at ISSCC
- Micron announced Gen 2 will be shipping end of 2016
- Hynix is sampling 48L 3D NAND
- Toshiba/WDC announced 64L 3D available end of 2016
- 48L today, 64L is coming soon.
3D Process Technologies

- Samsung NAND process is shipping in volume and has multiple teardowns to show capability and changes over time.
- Geometry terms like 40nm or 20nm are not useful. Architecture is too complex for simple analysis like this.
  - Samsung VNAND was called 40nm. It's actually 20nm or 60nm or 80nm
- Layers, spacing, architecture needs to be analyzed to understand scaling
- Samsung 48L cross sections and analysis have appeared in EEtimes.
- Micron 32L device has cross sections now publicly available
  - It is clearly floating gate and the cell is significantly different from Samsung cross sections.
  - It would appear vertical spacing of cells is very aggressive
  - Periphery below array provides increased efficiency
- No public cross sections of Toshiba/WDC/Hynix are available

- So when are these technologies going to ramp into volume??
**FMS 2013: Return-On-Investment on NAND Scaling**

**Unit cost is very high to start**

- High wafer cost
- Low output/yield
- These improve continuously over time

We convert line fully when new cost is lower than old
Example of 3D Layer Impact

- Average of all densities and vendors
- Die size/yield is determining factor
- ~60% Reduction in cost in 3 years
August 2016 Cost Summary ($/GB)
Specific Announced or Reported Products

- Modeled cost
- Based on data for each product
- Each product at different maturity

2016 Planar MLC
Impact of Cost on 3D Ramp

- **3D NAND allows NAND cost reduction to continue.**
  - 25%-35% per year is typical for NAND
  - There will not be a non-linear cost reduction with 3D NAND
    - 3D NAND will ramp over time, cost will improve continuously

- **TLC will potentially lead to significant cost reduction.**
  - TLC is a 25-30% cost reduction to MLC.
  - Impact seen as SSDs, Cell phones convert from MLC to TLC

- If more applications can use TLC with 3D NAND, Cost benefits increase
2D to 3D Transition

2015 Share

- Samsung: 31%
- Toshiba: 11%
- SanDisk: 14%
- Micron: 15%
- SK Hynix: 21%
- Intel: 8%

X %3D By vendor

2017 3D NAND Bit%

- 3D NAND: 62%
- Planar: 38%
3D NAND Bit% Over Time
Total Shipped for Each Year

- 3D NAND Exceeds 50% in 2018
SSD Market Penetration

- SSDs are growing but still trail HDD
- Will there be a tipping Point?
- Will it saturate?

- Gartner, IDC, DE, Internal
- Notebook includes 2:1s with SSD
- Does not include notebooks with eMMC (No SSD/HDD)
SSD Form Factor Guess-imates

**FUTURE**
- Move from HDD FF
- M.2 Dominates (Client/Enterprise)
- BGA for 2:1/Notebook
- AIC for Accelerators

- M.2 for all applications from Ultramobile to Enterprise
- BGA is cost effective solution for Ultramobile 2:1s, Tablets, Phablets, Limited suppliers before. Now offered by multiple SSD OEMs and OSATS

Source: MKW Ventures estimates

*DIMMS not included
3D NAND: Challenges
3D NAND Challenges

- Capital Intensive (New Tools/Fabs)
- Product and fab expense (conversions and qualification)
- Processing
  - Defects/Yield, Etch, deposition
- Limit on layer count
  - Aspect ratio, String Resistance
- Being efficient at lower density
  - Layout overhead
  - Periphery under array vs parallel
DRAM scaling (DRAM:NAND ratio)

- Example: Enterprise SSD’s typically maintain DRAM:NAND ratio at 1:1000
- NAND Scaling
  - 3D NAND can scale in layers, x-y dimension
  - MLC → TLC transition in 3D NAND with QLC intro expected in 2\textsuperscript{nd}/3\textsuperscript{rd} gen 3D
- DRAM Scaling
  - Unclear if DDR4 will pervasively introduce 16Gb
  - Timing of DDR5 ramp is yet evolving
Next Generation Memories

Size of bubble represents cost/bit (not to scale)

Write/Read Ratio

1ns 10ns 100ns 1µs 10µs 100µs 1ms 10ms

SRAM  DRAM  MRAM  RRAM  PCM  NAND  HDD

MLC  SLC  MLC  SLC

Flash Memory Summit 2016
Santa Clara, CA
### New Memory Technologies

<table>
<thead>
<tr>
<th></th>
<th>Latency</th>
<th>Density</th>
<th>Cost</th>
<th>HVM ready</th>
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<tbody>
<tr>
<td>DRAM</td>
<td>*****</td>
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<td>***</td>
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<tr>
<td>NAND</td>
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<td>*****</td>
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<tr>
<td>MRAM</td>
<td>*****</td>
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<tr>
<td>PCM (Micron)</td>
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<tr>
<td>3DXP</td>
<td>***</td>
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<td>*</td>
</tr>
<tr>
<td>ReRAM</td>
<td>***</td>
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</tbody>
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- **3D XPoint** Announced in July 2015: 128G, “1000x faster, 10x denser, 1000x better endurance”
- **Revenue projected to grow significantly starting end of 2016**
  - Session 203A (RRAM), 301C (3d Xpoint)
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THANKS!

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