Storage Class Memory:
Learning from 3D NAND

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This presentation contains forward-looking statements that involve risks and uncertainties, including, but not limited to, statements regarding our product and technology positioning, the anticipated benefits of our new technologies and transitioning into 3D NAND. Forward-looking statements should not be read as a guarantee of future performance or results, and will not necessarily be accurate indications of the times at, or by, which such performance or results will be achieved, if at all. Forward-looking statements are subject to risks and uncertainties that could cause actual performance or results to differ materially from those expressed in or suggested by the forward-looking statements.

Additional key risks and uncertainties include the impact of continued uncertainty and volatility in global economic conditions; actions by competitors; difficulties associated with go-to-market capabilities and transitioning into 3D NAND; business conditions; growth in our markets; and pricing trends and fluctuations in average selling prices. More information about the other risks and uncertainties that could affect our business are listed in our filings with the Securities and Exchange Commission (the “SEC”) and available on the SEC’s website at www.sec.gov, including our and SanDisk’s most recently filed periodic reports, to which your attention is directed. We do not undertake any obligation to publicly update or revise any forward-looking statement, whether as a result of new information, future developments or otherwise, except as otherwise required by law.
The Western Digital Family of Brands

Bringing the Possibilities of Data to Life
LTM revenues based on most recent public filings and Wall Street research; Western Digital and SanDisk LTM as of 4/1/2016; Toshiba represents March 2016 LTM revenue.
40 Zettabytes of data in 2020 or 40 Billion Terabyte Drives of Data

Moving Mountains of Data

Core Register  Core L1 Cache  Core L2 Cache  Shared L3 Cache  DRAM

<table>
<thead>
<tr>
<th>Size</th>
<th>64KB</th>
<th>256KB</th>
<th>2-4MB</th>
<th>16-128GB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>1ns</td>
<td>3-10ns</td>
<td>10-20ns</td>
<td>50-100ns</td>
</tr>
<tr>
<td>Cost</td>
<td></td>
<td></td>
<td></td>
<td>100x</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Storage Type</th>
<th>Size</th>
<th>Speed</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flash</td>
<td>512GB-4TB</td>
<td>100,000ns-2,000,000ns</td>
<td>5x</td>
</tr>
<tr>
<td>HDD</td>
<td>4-16TB</td>
<td>5-10,000,000ns</td>
<td>1x</td>
</tr>
</tbody>
</table>

Source: Western Digital estimates
The Data Bottleneck

Conventional Applications
- <1% misses

BIG DATA Applications
- >90% misses

System Energy / Time Consumption
- 10% data transfer
  - Compute
  - Memory Access

Cache Access
- <1% misses
  - Hits
  - Misses

Source: S. Wong, CCD 2015 presentation

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Data Centric Computer Architectures

Rack Scale Architecture

- 100G Ethernet
- Pooled SCM
- Server Nodes
- Server Nodes
- Server Nodes
- Pooled Flash
- JBOD

Cheap CPUs Around PB of SCM

- SRAM / eDRAM
- DRAM / MRAM
- CPU / CS
- DDR / New
- SCM Controller
- SSD CNTLR
- PCIe-NVMe
- NAND

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## Moving Mountains of Data

### Core
- Register
- L1 Cache
- L2 Cache
- L3 Cache

### DRAM
- Size: 16-128GB
- Speed: 50-100ns
- Cost: 100x

### Storage Class Memory
- Size: 128GB-1TB
- Speed: 250-5,000ns
- Cost: 20-25x

### Flash
- Size: 512GB-4TB
- Speed: 100,000ns-2,000,000ns
- Cost: 5x

### HDD
- Size: 4-16TB
- Speed: 5-10,000,000ns
- Cost: 1x

**Source:** Western Digital estimates
SCM Compute Applications / Market Evolution

Fast Storage
DRAM Extension
DRAM Displacement
Universal Memory

Source: Western Digital estimates
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Memory & Storage Hierarchy

- **Storage**
  - HDD
  - NAND
- **Memory & Storage Hierarchy**
  - Volatile
    - DRAM
    - SRAM
  - Non-Volatile
    - PCM
    - CBRAM
    - ReRAM
    - STT-MRAM

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The FAB 4 of Semiconductor Nirvana

Cost  Scalability  Scale  Ecosystem

Case Study
2D NAND ➔ 3D NAND
Transition
In NAND We Trust: More than Moore

OVER
50,000X
Cumulative cost reduction over 20 years*

Note: Images are not to scale
*Based on historical SanDisk NAND pricing 1992*

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How Tall Would it Be?

Mount Kilimanjaro
19,340ft

Eiffel Tower
984ft

Burj Khalifa
2717ft

Mount Fuji
12,388ft

Number of wafers produced in 2016 in Yokkaichi

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2D NAND Architecture
Scaling Stopped the Music for 2D NAND!

- Cost of lithography
- Density of electron storage in the floating gate
- Proximity effects from adjacent cells

3D NAND: A necessary revolution

Case Study
2D NAND ➔ 3D NAND
Transition
3D NAND Cell

- Charge Trap Layer
- Poly-Si Body
- Gate
- Control Gate
- SG
3D NAND Architecture

SGD

WL

SGS

Memory Holes

Source Plate

Memory Cell
Proximity Effect in BiCS

- WL Direction
- BL Direction

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Our Next Generation 3D NAND Technology is Here

- World’s **first 64-layer 3D NAND** architecture
- Capacities up to **512Gb** on a single chip
- **Smallest** 256Gb chip in the industry
- **OEM** sampling in the current quarter; retail shipments expected in calendar Q4 2016

**NAND Cost Scaling Continues**
The BiCS Scaling March

BiCS1

BiCS2 48L

BiCS3 64L

BiCS4

BiCS5
Manufacturing Scale:
Mountains of wafers being converted to 3D NAND

Industry 2D NAND vs. 3D NAND Bit Output

Industry bit cross-over in mid-2017
Cost Scaling for SCM Market Adoption

Note: Technology transition cadence assumed 18 months for all technologies ReRAM & 3DXP greenfield fabs, NAND & DRAM existing fabs

* DRAM data source: IDC ASP forecast with 45% GM assumed
** 13 nm: assumes EUV @ 1.4x i-ArF capex cost, 2160 w/day
3D Technologies for SCM

- Cell and Materials
- Selector
- Process Architecture
- Product
- Ecosystem
Cross Point Memory Implementations

8-layer 3D cross-point array memory ca. 2002

32Gb, 24nm, 2-layer 3D cross-point array ReRAM 2013
3D Resistive RAM as Storage Class Memory

Latency & Endurance

Lower Cost

Ecosystem Support

Scalability with 3D

Scale & Capital Efficiency

ReRAM is Western Digital’s Choice for SCM
Summary

Western Digital + SanDisk: A leading combination

Data explosion enabled by edge devices

3D NAND: A revolution underway

Lower latency memory component needed for data-centric computing

3D ReRAM is a scalable SCM solution
Bringing the possibilities of data to life.