![Western Digital logo]

Storage Class Memory:
Learning from 3D NAND

Siva Sivaram

EVP of Memory Technology,
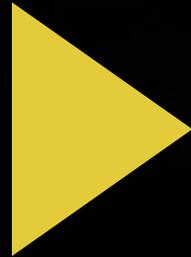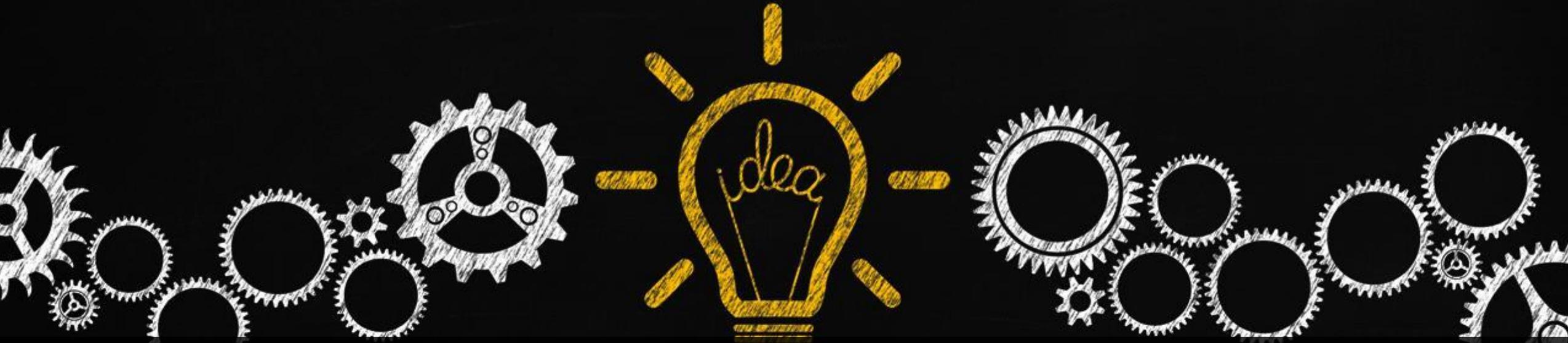Western Digital Corporation

August 9, 2016

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Forward-Looking Statements

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.
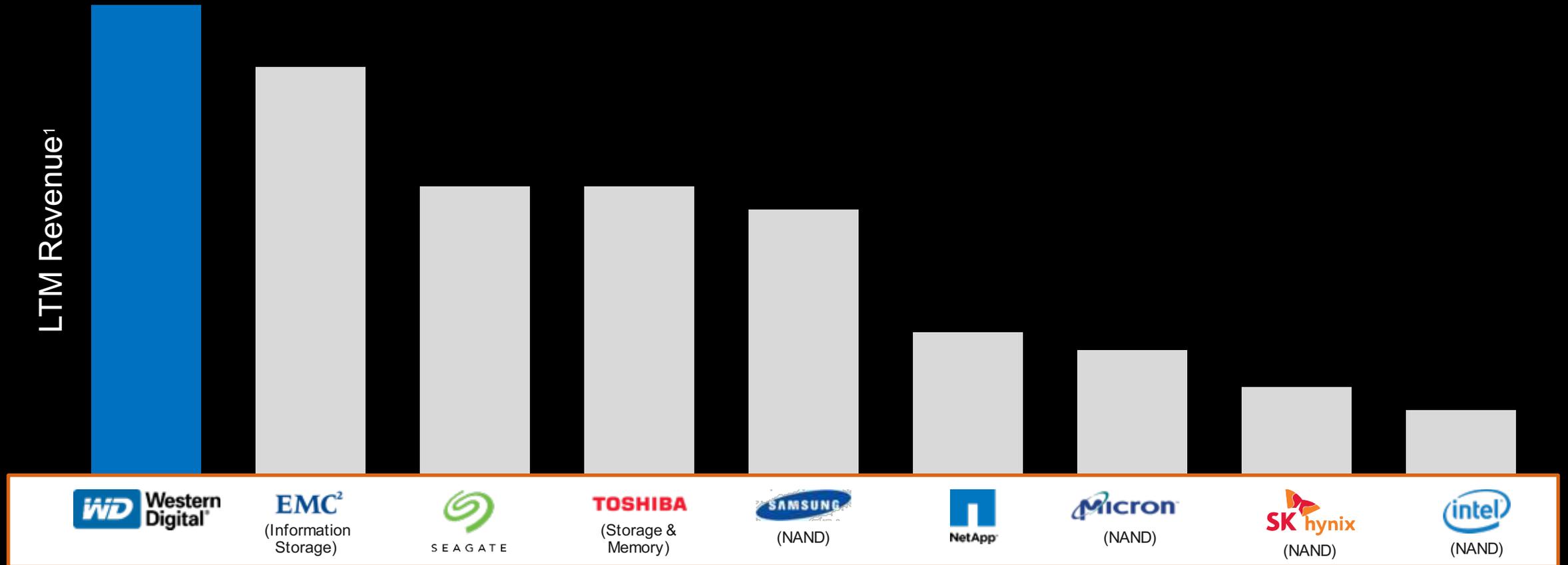
Additional key risks and uncertainties include the impact of continued uncertainty and volatility in global economic conditions; actions by competitors; difficulties associated with go-to-market capabilities and transitioning into 3D NAND; business conditions; growth in our markets; and pricing trends 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.
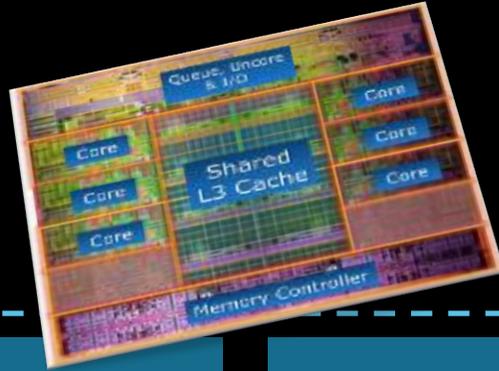
The Western Digital Family of Brands

Bringing the Possibilities of Data to Life

A Global Leader in Storage Technology

LTM Revenue[1]

WD Western Digital®	EMC² (Information Storage)	SEAGATE	TOSHIBA (Storage & Memory)	SAMSUNG (NAND)	NetApp®	Micron (NAND)	SK hynix (NAND)	intel (NAND)

[1] LTM revenues based on most recent public filings and Wall Street research;
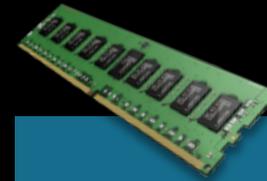Western Digital and SanDisk LTM as of 4/1/2016; Toshiba represents March 2016 LTM revenue.

40

Zettabytes of data in **2020**

or **40 Billion**
Terabyte Drives of Data

Western Digital

Moving Mountains of Data

	Core Register	Core L1 Cache	Core L2 Cache	Shared L3 Cache	DRAM
Size	64KB	256KB	2-4MB	16-128GB	
Speed	1ns	3-10ns	10-20ns	50-100ns	
Cost				100x	

	Flash	HDD
Size	512GB-4TB	4-16TB
Speed	100,000ns-2,000,000ns	5-10,000,000ns
Cost	5x	1x

Source: Western Digital estimates

The Data Bottleneck

Conventional Applications

BIG DATA Applications

Cache Access

<1% misses
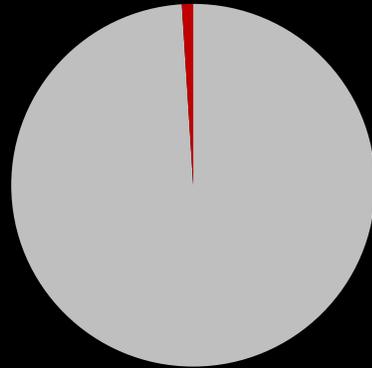
- Hits
- Misses
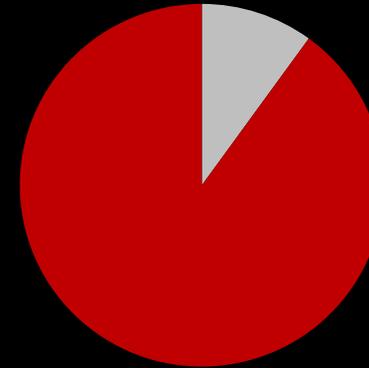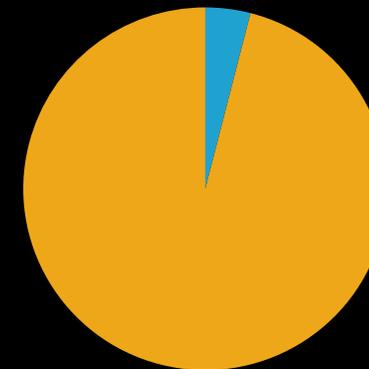
>90% misses

System Energy / Time Consumption

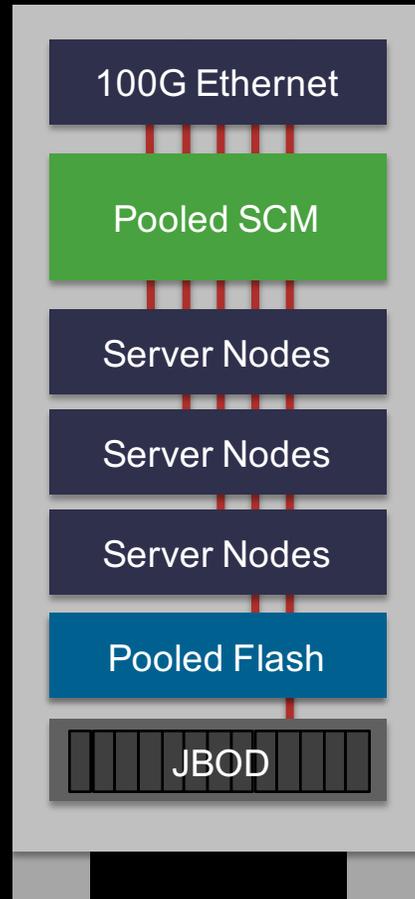10% data transfer
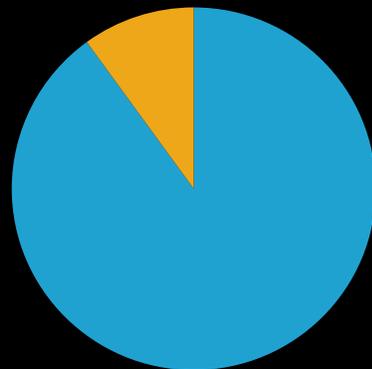
- Compute
- Memory Access

96% data transfer

Source: S.Wong, CCD 2015 presentation
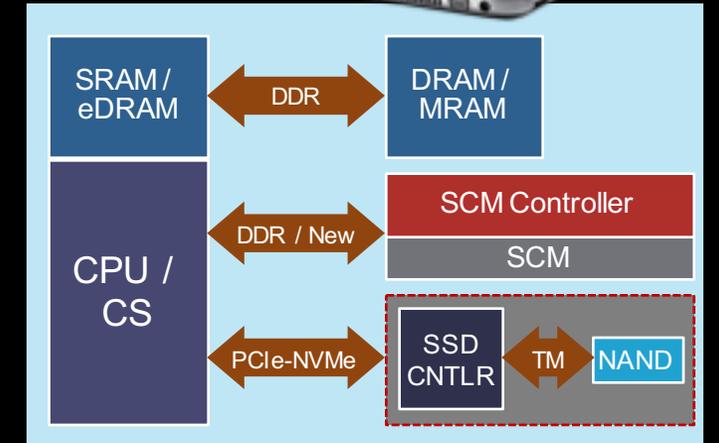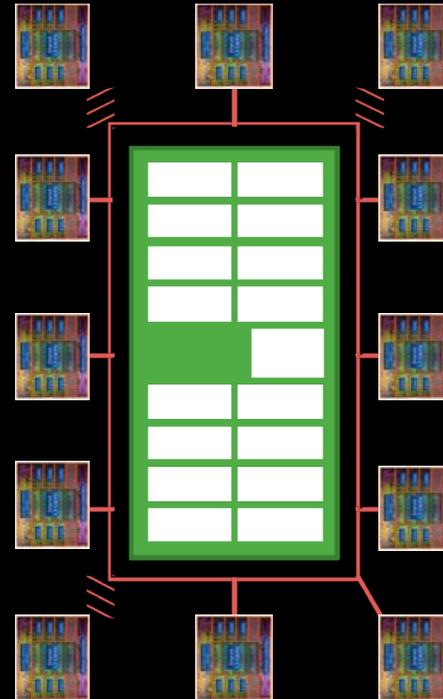
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Data Centric Computer Architectures

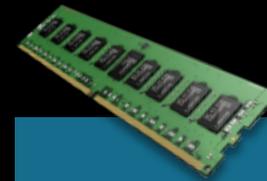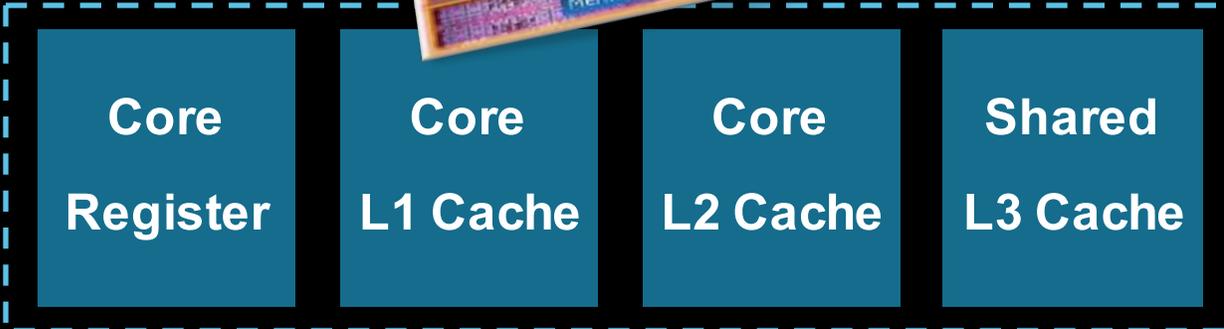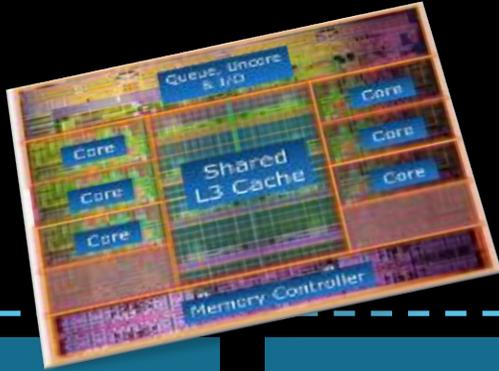**Rack Scale Architecture**

Cheap CPUs Around PB of SCM

eDRAM

AP

DDR / New

SCM Controller

SCM

100G Ethernet

Pooled SCM

Server Nodes

Server Nodes

Server Nodes

Pooled Flash

JBOD

SRAM / eDRAM

DDR

DRAM / MRAM

CPU / CS

DDR / New

SCM Controller

SCM

PCIe-NVMe

SSD CNTLR

TM

NAND

DRAM & NAND Cell Sizes

Cell size (nm²) / L

DRAM

NAND x2

NAND x3

30X

Moving Mountains of Data
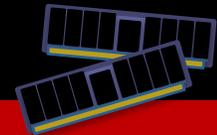
	Core Register	Core L1 Cache	Core L2 Cache	Shared L3 Cache	DRAM	Storage Class Memory	Flash	HDD
Size	64KB	256KB	2-4MB	16-128GB	128GB-1TB	512GB-4TB	4-16TB
Speed	1ns	3-10ns	10-20ns	50-100ns	250-5,000ns	100,000ns-2,000,000ns	5-10,000,000ns
Cost				100x	20-25x	5x	1x

Source: Western Digital estimates

WD Western Digital®

SCM Compute Applications / Market Evolution

$10B Market
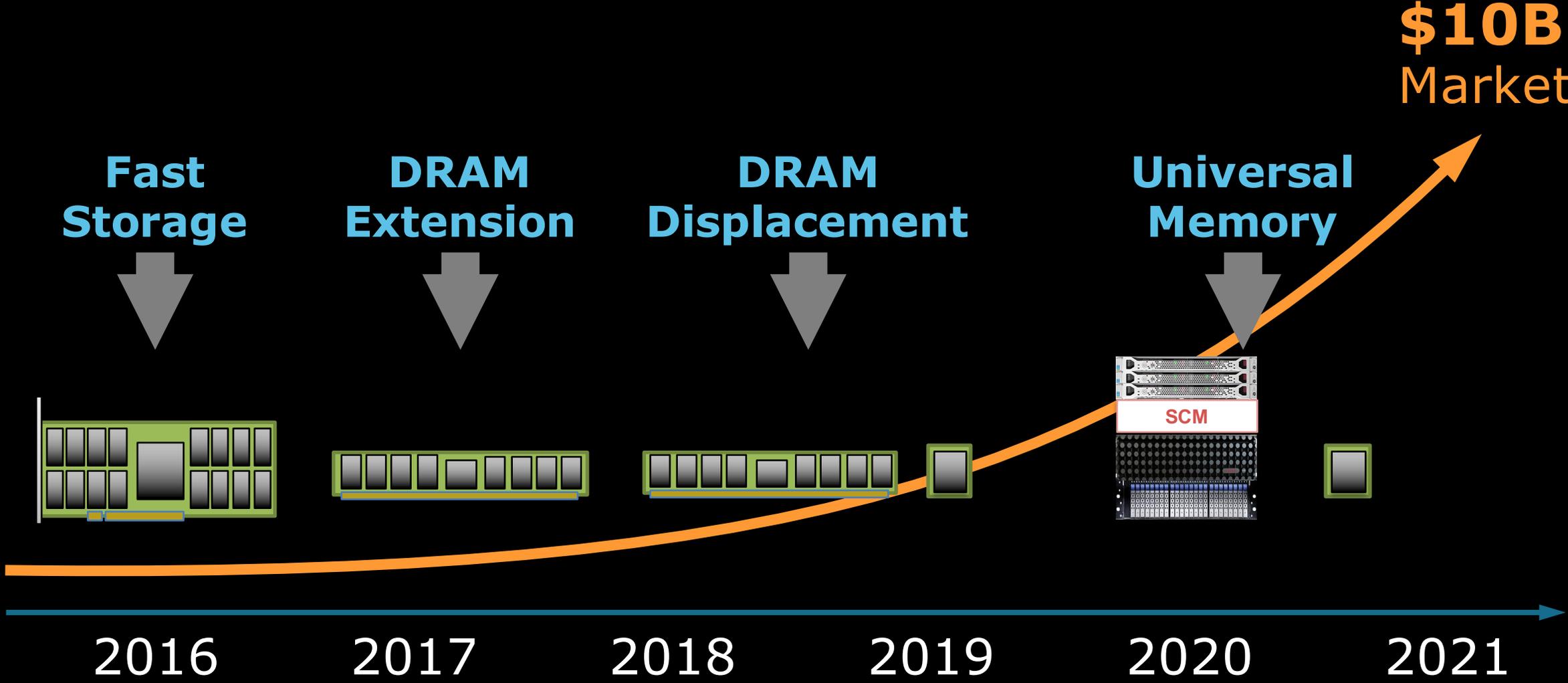
Fast Storage

DRAM Extension

DRAM Displacement

Universal Memory

SCM

2016   2017   2018   2019   2020   2021

Source: Western Digital estimates

Western Digital

Memory & Storage Hierarchy
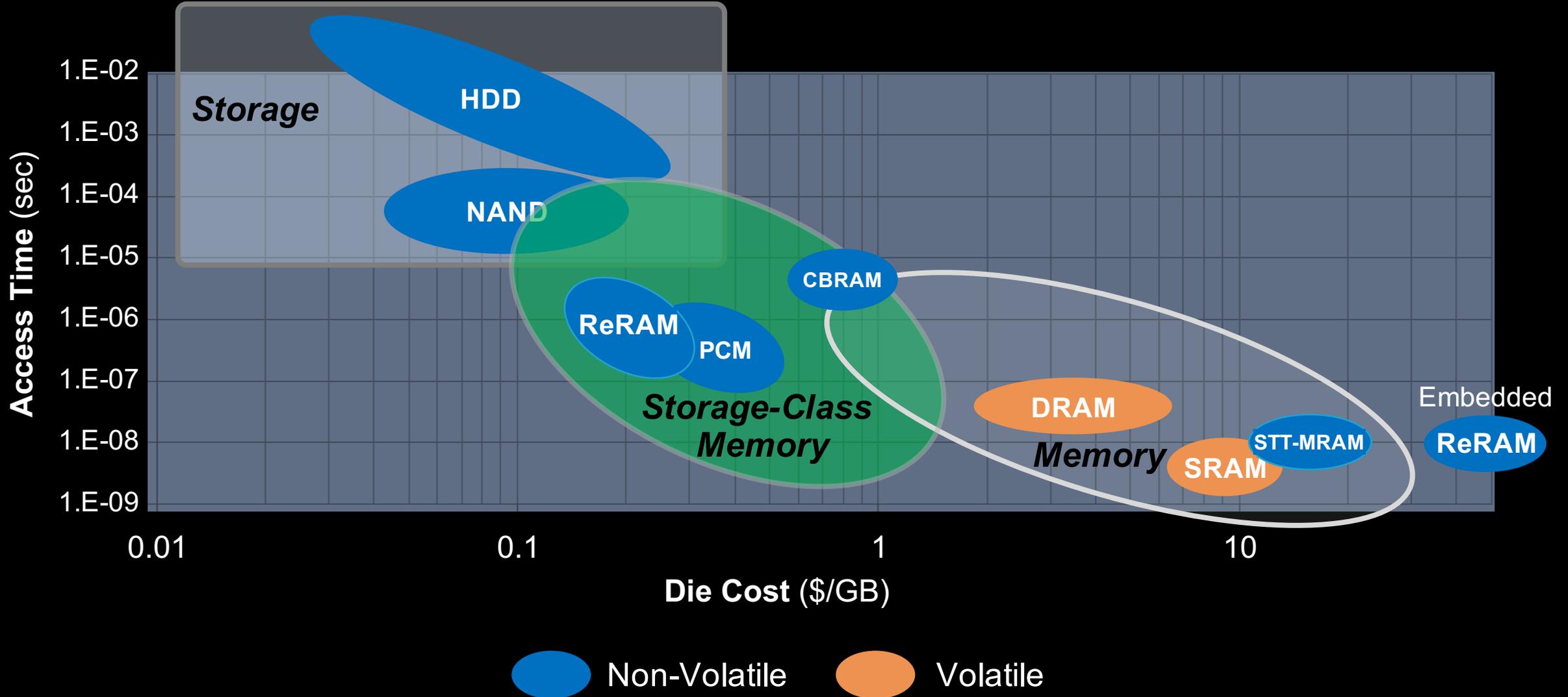
The FAB 4 of Semiconductor Nirvana

Cost Scalability Scale Ecosystem

WD Western Digital®

In NAND We Trust: More than Moore

Cost

1Gb,
X2-160nm

2Gb,
X2-130nm

4Gb,
X2-90nm

8Gb,
X2-70nm

16Gb,
X3-56nm

32Gb,
X3-43nm

64Gb,
X3-32nm

64Gb,
X3 24nm

128Gb,
X3 19nm

128Gb,
X3 1Ynm

128Gb,
X3 1Znm

OVER

50,000X

Cumulative cost reduction over 20 years*

2001 2003 2005 2007 2009 2011 2013 2015 2017 2020
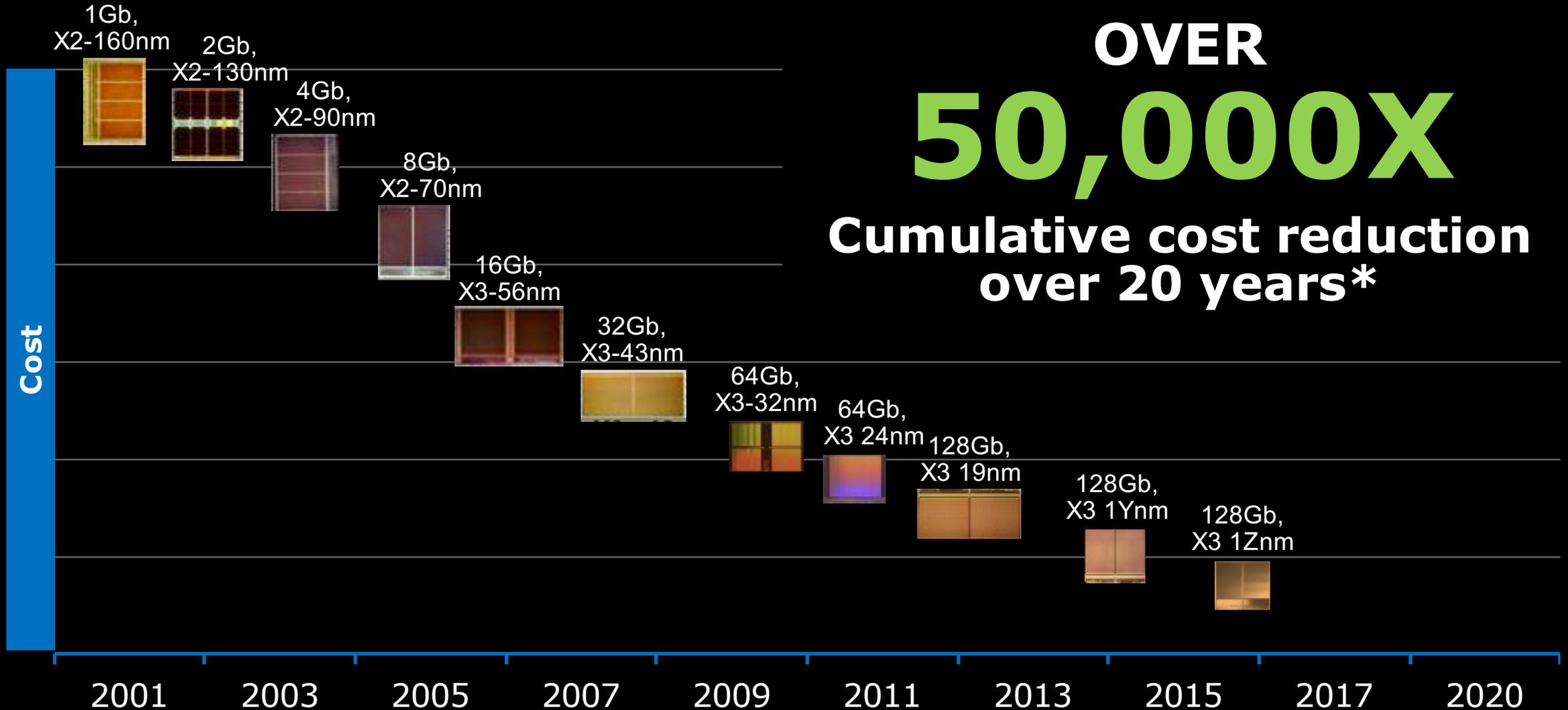
Note: Images are not to scale   *Based on historical SanDisk NAND pricing 1992*

When the Chips are Down, the Wafers are Up!

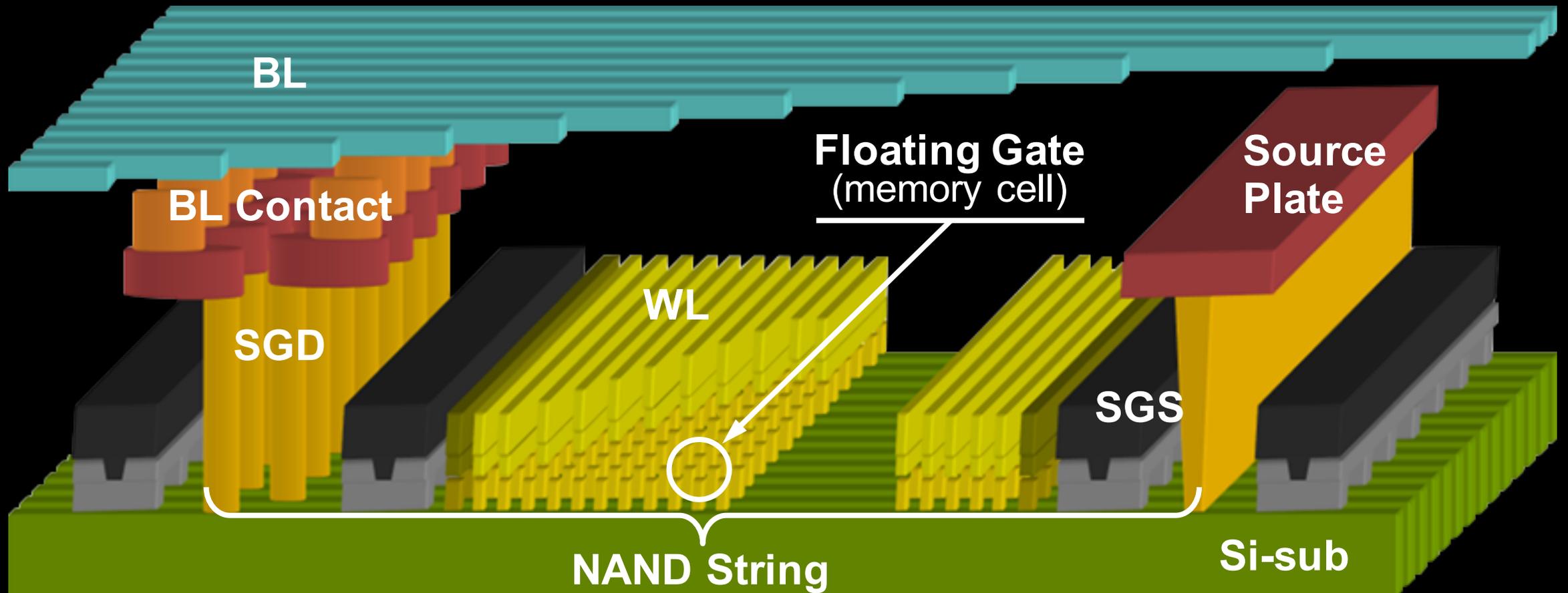## How Tall
Would it Be?

Mount Kilimanjaro
19,340ft

Number of wafers produced in 2016 In Yokkaichi

Eiffel Tower 984ft

Burj Khalifa 2717ft

Mount Fuji 12,388ft

WD Western Digital®

2D NAND Architecture

BL

BL Contact

Floating Gate
(memory cell)

Source
Plate

SGD

WL

SGS

NAND String

Si-sub

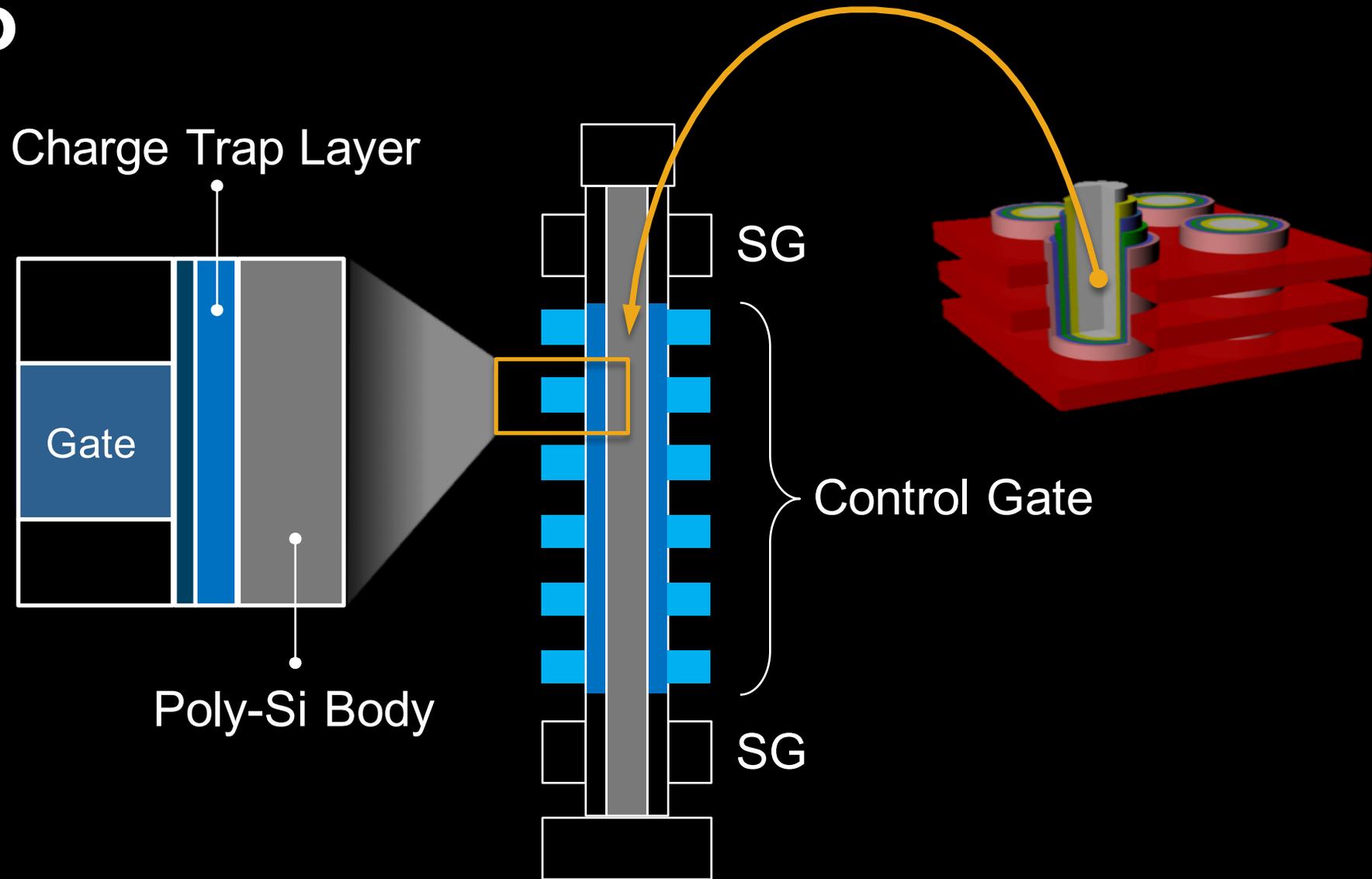## Case Study
2D NAND
➔ 3D NAND
Transition

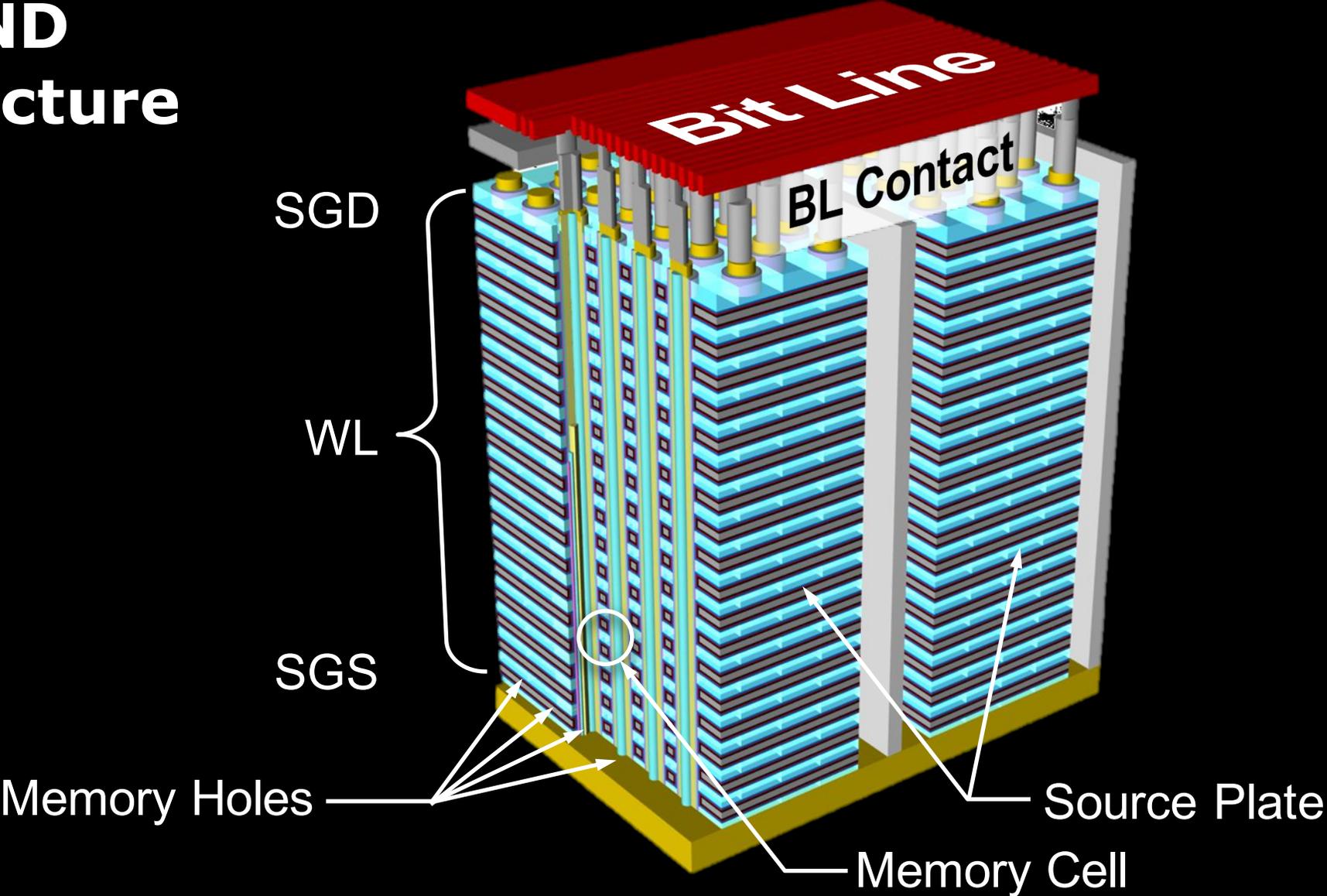# Scaling Stopped the Music for 2D NAND!

– Cost of lithography

– Density of electron storage in the floating gate

– Proximity effects from adjacent cells
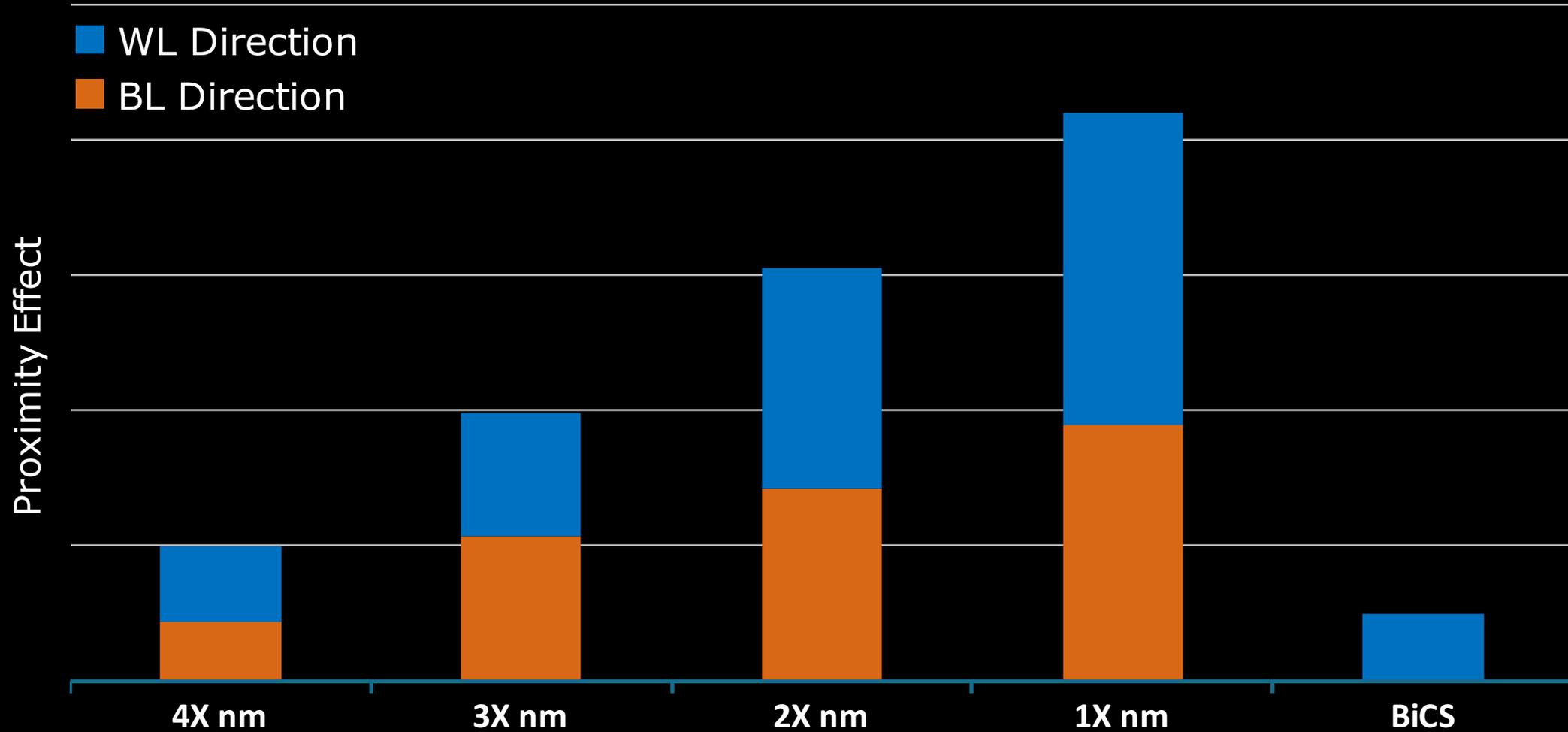
3D NAND: A necessary revolution

3D NAND Cell

Charge Trap Layer

Gate

Poly-Si Body

SG

SG

Control Gate

3D NAND Architecture

SGD

WL

SGS

Bit Line

BL Contact

Memory Holes

Memory Cell

Source Plate

Proximity Effect in BiCS

Our Next Generation 3D NAND Technology is Here
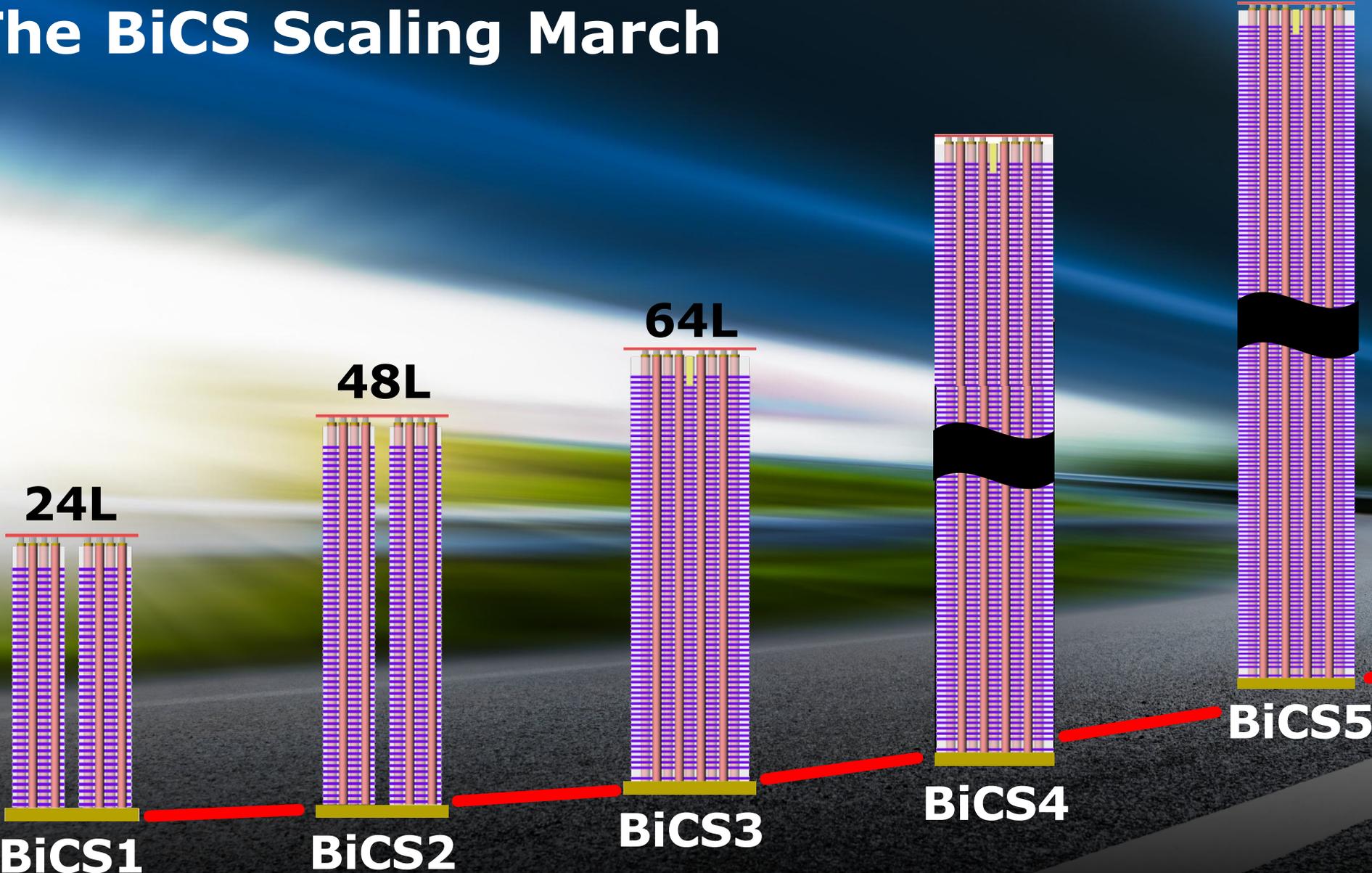
World's **first 64-layer 3D NAND** architecture

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
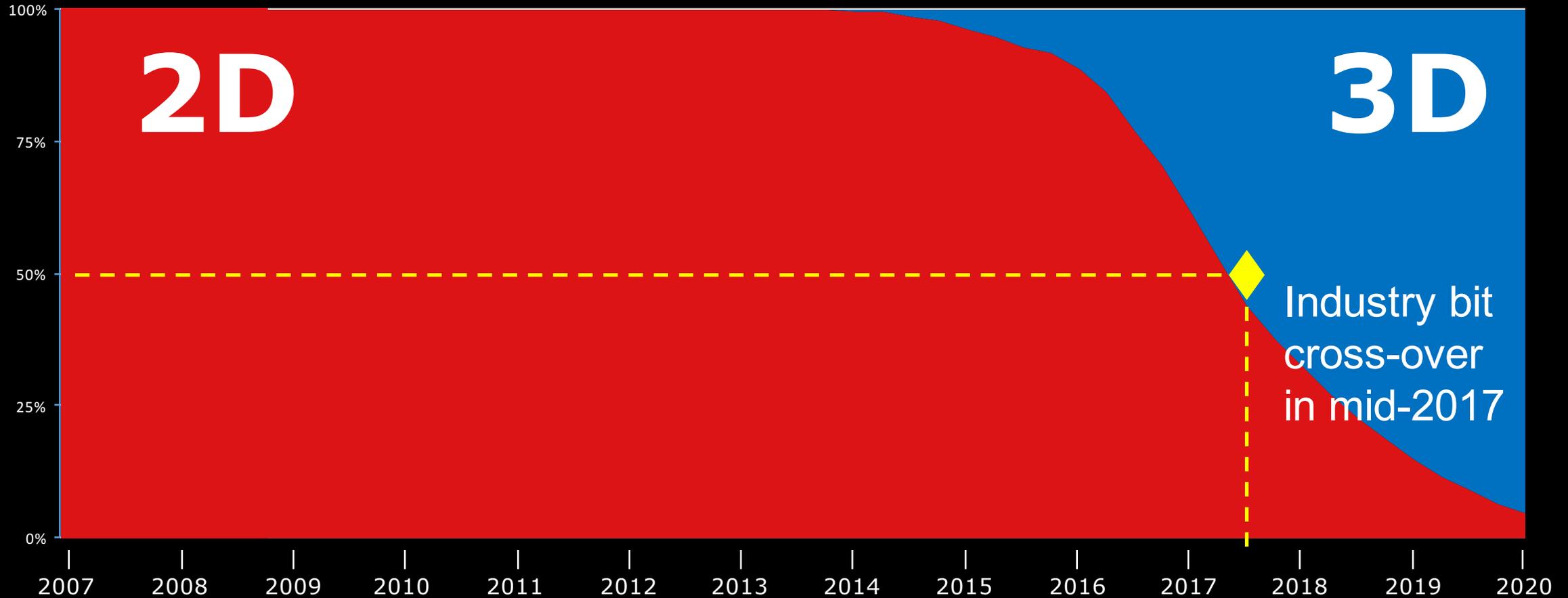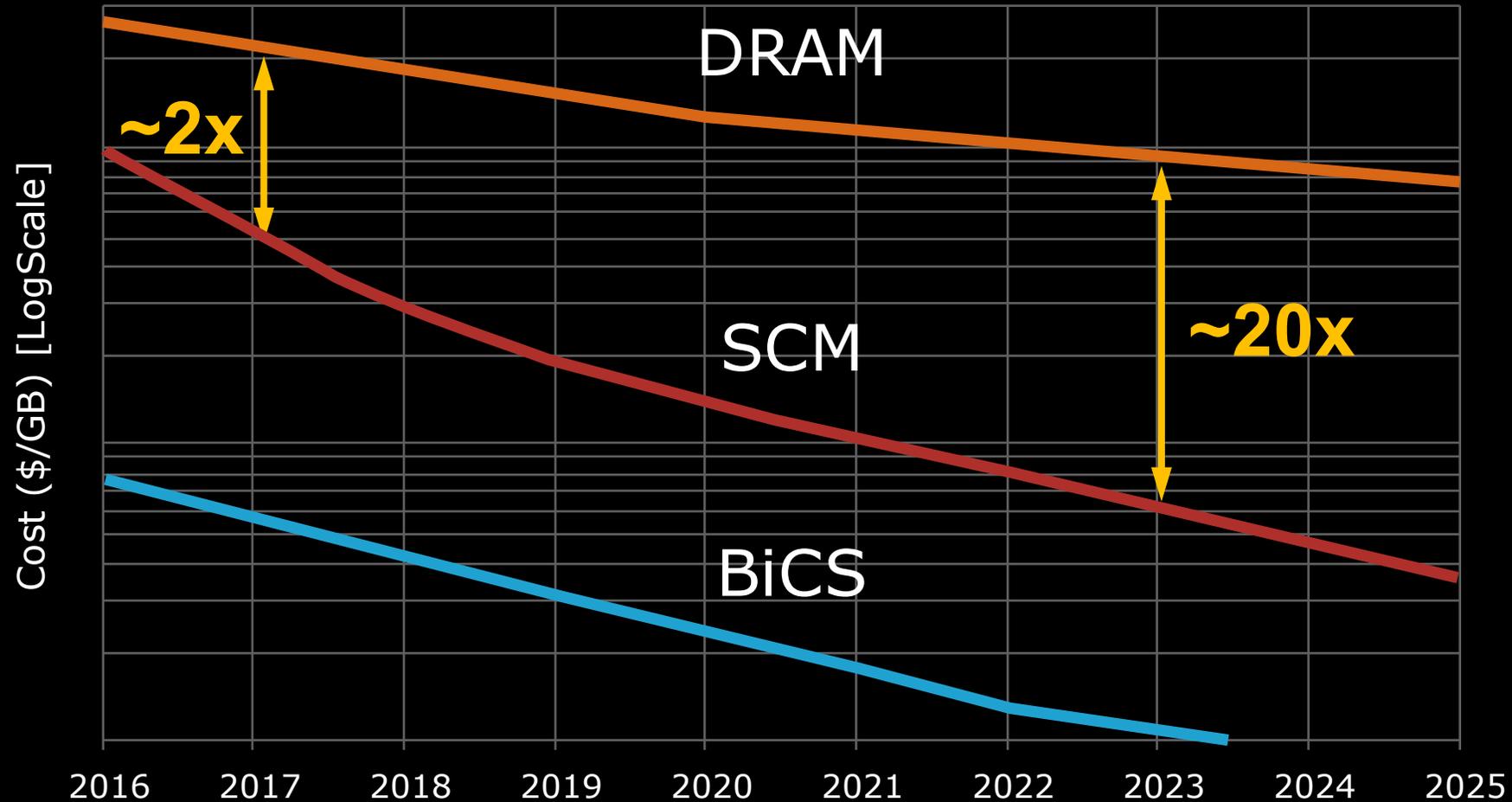
NAND Cost Scaling Continues

The BiCS Scaling March

24L

48L

64L

BiCS1

BiCS2

BiCS3

BiCS4

BiCS5

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

Industry 2D NAND vs. 3D NAND Bit Output

2D

3D

Industry bit
cross-over
in mid-2017

Cost Scaling for SCM Market Adoption

DRAM

SCM

BiCS

~2x

~20x

Cost ($/GB) [LogScale]

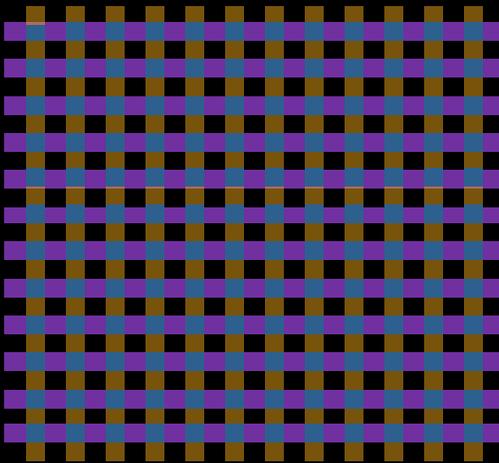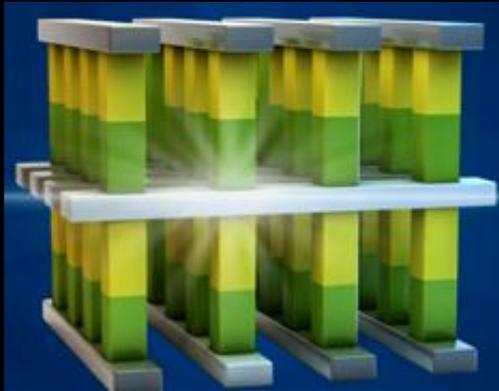2016 2017 2018 2019 2020 2021 2022 2023 2024 2025

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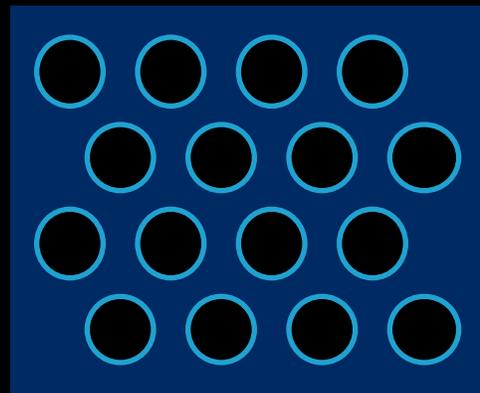ReRAM & 3DXP greenfield fabs, NAND & DRAM existing fabs

* 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
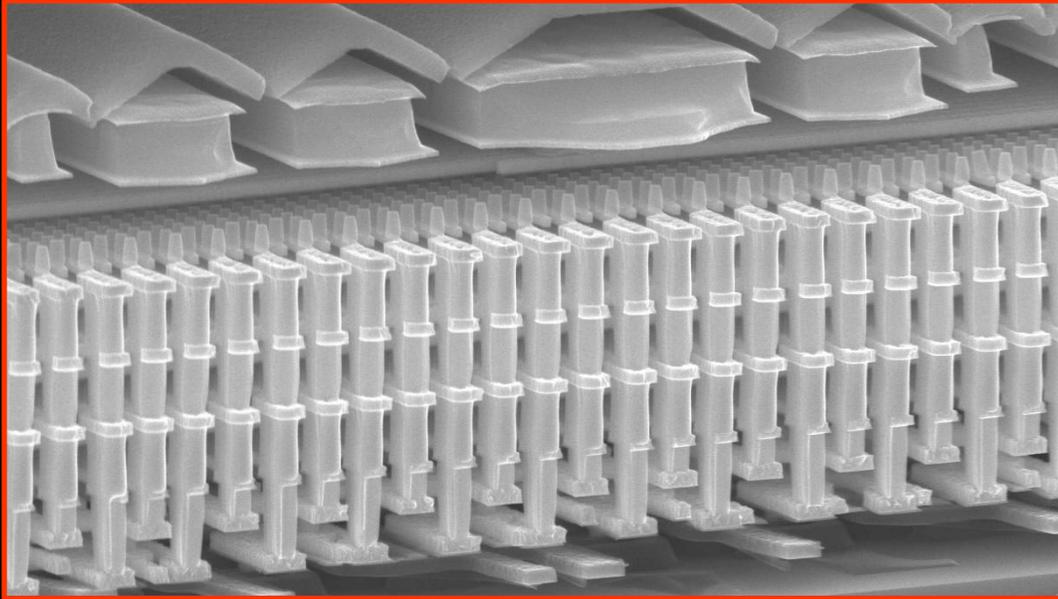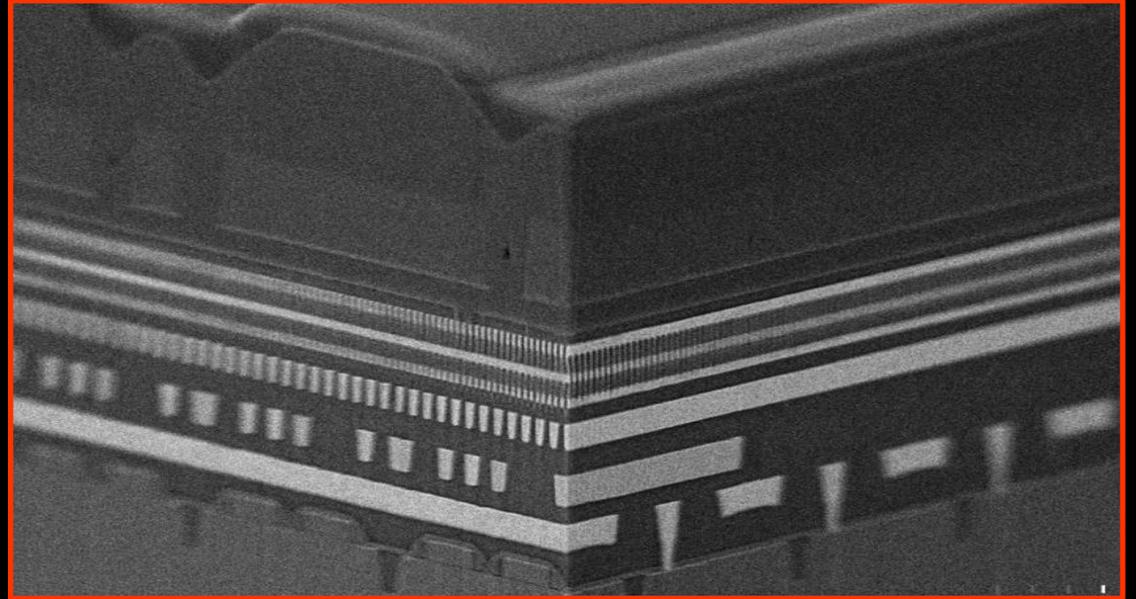
3D XPoint

3D NAND

- 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

3D ReRAM

Ecosystem Support

Scalability with 3D

Scale & Capital Efficiency

ReRAM is Western Digital's Choice for SCM
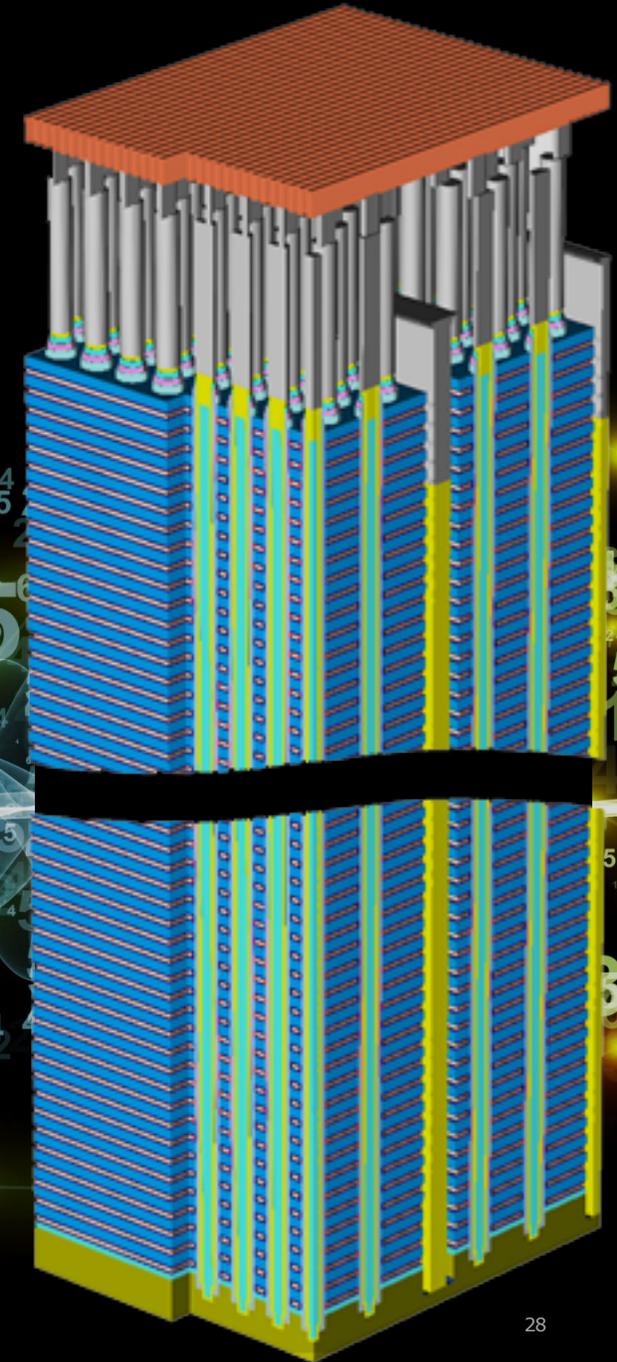
WD Western Digital®

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

Western Digital®

Bringing the possibilities
of data to life.