Western Digital

Technology Brief

Next-Generation Technologies for a New Decade of Big Data

Building on a Foundation of Technology Leadership, Timely Investments and Proven Execution

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Forward-looking Statements

This document contains forward-looking statements that involve risks and uncertainties, including, but not limited to, statements regarding our enterprise capacity hard drive products and technology positioning, the anticipated benefits of our technologies, and customer acceptance and adoption of the technologies. 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 implementing new HDD technologies; 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 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.

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“The value and intelligence that can be extracted from Big Data, and other, large data generating applications, has created strategic opportunities for HDD capacity expansion in the enterprise.”

Introduction

Data is the ‘life-blood’ of an organization and the key asset that they want to keep around for years. It must be easily accessible, secured, and reliable within an enterprise so it can be processed for real-time use, or analyzed in the future to extract further value or intelligence. It is for these reasons, and others (such as legal, regulatory, due diligence, etc.), why organizations invest in their data. The information extracted can lead to better business decisions, improved organizational processes, advanced technologies, and maximized returns.

The world is generating, preserving and analyzing more data per year than in the previous ten years combined – and is expected to more than double each year going forward. Over 163 zettabytes of digital data is forecasted to be generated by 2025[1] - a 10x growth from 2016. That’s a lot of data being generated by billions of people, using millions of apps, from billions of devices.

PCs, laptops, smartphones and tablets generate most of today’s data, but tomorrow’s data will come from connected and autonomous vehicles, factory robots and machine sensors, surveillance systems and drones, health and wellness wear-ables, and many more -- creating a need for efficient storage devices with much larger capacities.

163 zettabytes of digital data by 2025

The value and intelligence that can be extracted from Big Data, and other large data generating applications, has created strategic opportunities for HDD capacity expansion in the enterprise, and a challenge that Western Digital has invested billions of dollars to pursue.

By delivering the best and most stable helium-sealed HDD environment, with improved mechanical head positioning through multi-stage micro actuation, Western Digital has delivered higher capacities with each product generation.

As Western Digital develops the head assemblies for its leading helium HDD portfolio, the use of the Damascene process, coupled with energy-assisted magnetic recording technology, will enable the company to deliver even higher HDD capacities in the future, setting standards for others to follow.

Western Digital not only defines the future of hard drives, but has created innovative solutions by making prudent technology choices, investing in multiple parallel technologies, and delivering products to market with exceptional quality and reliability. This disciplined approach to solving industry problems, such as capacity expansion, will evolve the hard drive market for the next decade, and beyond.

[1] *Source: IDC Data Age 2025 (March 2017)*

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"Western Digital invested in, designed, and built a fundamentally sound helium-based hard drive platform much earlier than its competitors, and has delivered continual improvements each generation."

Western Digital's HGST-branded Ultrastar®Hs14 helium-sealed HDD

Western Digital's HGST-branded Ultrastar® He12 helium-sealed HDD

Helium-Sealed Technology

The data storage industry is undergoing a major shift in which new market segments and storage tiers are emerging, creating high demand for scalable, mass storage at cost-effective prices. The ***Capacity Enterprise Hard Drive*** segment is currently experiencing a 40% compound annual growth rate (CAGR) in petabytes stored.

Helium-sealed drives are part of this segment and represent one of the most significant storage technology advancements in decades. Western Digital's heritage in HDD development pioneered helium-sealed drives with the introduction of HelioSeal® technology in 2013 (under the HGST brand).

HelioSeal is the foundational building block for Western Digital's helium-sealed drive portfolio, with four successful generations of drives delivered to date, representing a solid and stable field-proven design. Over 20 million HelioSeal-based HDDs have been shipped to date worldwide.

Helium-sealed technology hermetically seals the drive housing with an inert gas (at one-seventh the density of air). The less dense atmosphere enables thinner disks to be used, as well as more disks in number, delivering higher capacities in the same physical form factor.

Less air friction also means less power required to spin the disks, reducing total cost of ownership (TCO). As hermetically sealed drives reduce air turbulence, the internal mechanisms are less susceptible to corrosion and humidity changes, delivering a higher reliability drive versus air-based devices.

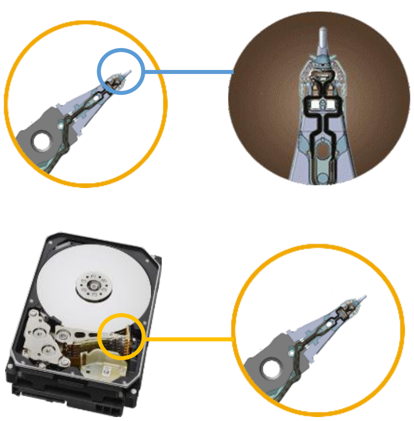
With the understanding that helium-sealing HDDs is a core technology that can keep pace with the value and growth of data, Western Digital invested in, designed, and built a fundamentally sound helium-based hard drive platform much earlier than its competitors, and has delivered continual improvements each generation.

In the third generation Ultrastar® He10 HDD (10TB[2] capacity), for example, connector pins with no through-holes were used to improve the integrity of the seal and mitigate disk leakage. In the fourth generation Ultrastar He12 HDD (12TB capacity), an eighth disk was added, enabling a capacity increase to 12TB, as well as development of an industry-leading 14TB shingled magnetic recording (SMR) drive.

Western Digital is committed to deliver more capacity-enriched helium HDDs in the future, based on proven and successful HelioSeal technology.

[2] One GB is equal to one billion bytes and one TB equals 1,000GB (one trillion bytes) when referring to hard drive capacity. Accessible capacity will vary from the stated capacity due to formatting and partitioning of the hard drive, the computer operating system, and other factors.

"The rock-solid Western Digital micro actuator design provides extremely accurate head positioning over the track, enabling increased track densities, while maintaining high reliability in noisy, high-vibration environments."



Western Digital's multi-stage micro actuator

Multi-Stage Micro Actuator

An actuator reads data from or writes data to a magnetic recording disk using a head assembly. The disk has spinning platters and a surface area that is divided into many sectors to store data. The head and actuator arm assembly, and its sliders, are moved by a servo motor to the location over the spinning platters from where data needs to be read or written.

As the number of tracks per inch (TPI) are increased, and, capacity is pushed to extremes, the finer the control of the head and actuator arm assembly must be. With a single stage actuator to move the head assembly across tracks, it becomes more difficult to position the head over the center of the track, and can impact performance adversely.

To address this challenge, Western Digital was the first to deliver multi-stage micro actuation in its third generation HelioSeal Ultrastar He10 HDD. This micro actuator adds a finer control stage that delivers greater accuracy of the head assembly over smaller, narrower tracks. When implemented into Western Digital's helium HDD portfolio, the micro actuator delivers better performance, data integrity and overall drive reliability versus single stage actuation, and supports track densities beyond 400,000 TPI.

As external disturbences (such as shock and vibration in the server rack) can cause track misalignments, the rock-solid Western Digital micro actuator design provides extremely accurate head positioning over the track, enabling increased track densities, while maintaining high reliability in noisy, high-vibration environments.

As a core hard drive technology, micro actuation has enhanced Western Digital's helium platform, demonstrating another good technology choice that the company made. With the addition of micro actuation, its mechanical head positioning technology is more advanced and better today than the competition, and works well in tandem with the other HDD core technologies.

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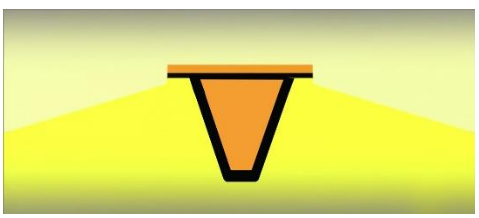
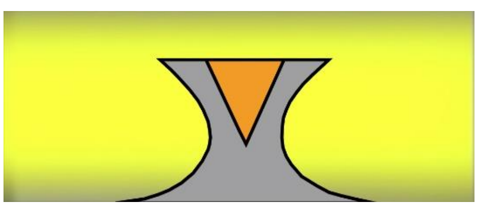
"Heads produced using the Damascene process provide a TPI advantage over the previously-used dry pole process, delivering the highest track density available and superior performance, with improved quality, better head write-ability, and higher head yields."



Tapered write head using the Damascene process



Milled write head using the dry pole process

Damascene Head Process

An HDD head assembly uses a magnetic field to read data from and write data to the surface of a magnetic recording disk. Electrical currents flow through a coil in the write head assembly that magnetizes a small area on the storage media, producing the magnetic field, enabling data to be recorded.

When bits are written, they are oriented on the disk by flipping polarity to either a 1 or 0. The bit density is defined by two important hard drive parameters: (1) bits per inch (BPI) along the track; and (2) tracks per inch. Multiplying the BPI by the TPI results in the disk's areal density -- or how much capacity per square inch is available on the disk's surface.

The higher the TPI, the more areal density and capacity per square inch that is available. Scaling is limited by the write-ability of the recording system and the track pitch, requiring a reliable, narrow write head, with tighter spacing, to achieve smaller tracks.

It was at this stage in its history that Western Digital was faced with a critical strategic decision on the direction to take, and investment to be made, in the head manufacturing process, to increase hard drive capacities in the future. As the gains from perpendicular magnetic recording (PMR) were slowing down, the decisions were to either invest substantial dollars in the Damascene head-making process for extending gains in PMR, or rely on large gains and early productization of heat-assisted magnetic recording (HAMR) technology.

Western Digital decided to invest in improving its current hard drive technologies and pursue multiple options for increasing enterprise capacities, versus relying solely on HAMR technology (as it continued to be challenged with complexity and reliability issues). The decision proved prudent and will lead the way for Western Digital to increase enterprise capacities over the next decade, without HAMR.

From internal testing, heads produced using the Damascene process provided a TPI advantage over the previously-used dry pole process, delivering the highest track density available and superior performance, with improved quality, better head write-ability, and higher head yields. A significant reduction in adjacent track interference (ATI), was also achieved using the Damascene process.

The main pole, and the structures of the write head in the Damascene process are shaped and tapered by depositing and etching magnetic and non-magnetic materials. This process also enables the formation of a full wrap-around shield that helps to focus the magnetic field on to the target area being written while reducing interference on adjacent tracks.

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"{Western Digital} produced several Hard drive innovations using the Damascene head-making process to obtain finer control of the head shape and dimensions when writing to a small, narrow track on disk."

Value of Damascene

Better geometric control	More gains More TPI
Features wrap-around shield	Less track interference
Enables complex head structures	Made MAMR possible
Finer tolerance control	Better head quality and higher yields

Damascene Head Process (continued)

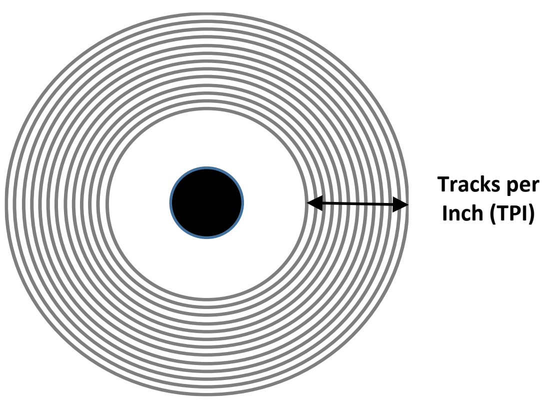
The multi-layer of materials deposited and plated into a head deliver finer control of its shape and dimensions, and the ability to create complex head structures using very thin layers of materials, with whatever shape is required.

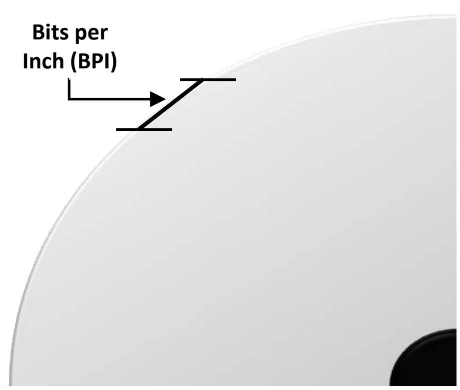
In the previously-used dry pole process, the main pole of the write head is shaped by ion milling. Side shields, along with trailing shields, are built within a non-flat topography. As side gaps are created through milling, the head shape and thickness control processes become more challenging than Damascene.

The dry pole process limits innovation that is possible through material and geometry changes. Used in semiconductor design, the Damascene process has many advantages including better control of the head geometry (affects areal density gains and helps mitigate interference from neighboring tracks), better scaling of the head dimensions (affects TPI and areal density), and better control of manufacturing process tolerances (affects head quality and head yields).

In quick review of the HDD core competencies driven by Western Digital, the company pioneered helium-sealed HDD technology -- was the first to deliver multi-stage micro actuation for better head positioning in a hard drive – and produced several hard drive innovations using the Damascene head-making process to obtain finer control of the head shape and dimensions when writing to a small, narrow track on disk.

The decision to improve current core HDD technologies, coupled with the successful development and execution of these technologies, position Western Digital as the leader in hard drives today, and the company that will deliver increased hard drive capacities in the future.





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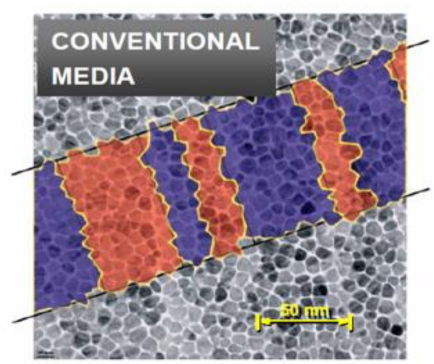
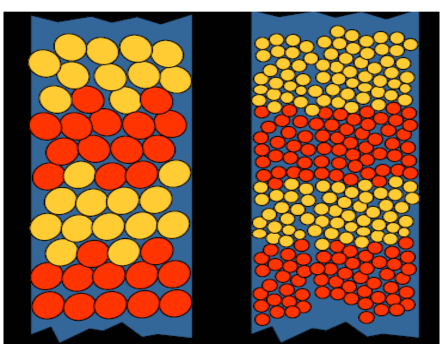
"In addition to significant costs, HAMR has engineering complexities and manufacturing challenges that need to be resolved before it can satisfy the reliability demands of today's data center."





Each bit is stored in magnetic grains within continuous magnetic film -- Increasing disk capacity requires smaller grains on the media, and a smaller head to magnetize the grains

Energy-Assisted Recording: HAMR vs MAMR

A narrow Damascene-made writing head provides fine control, high quality, improved head yields, and writes with a focused field, avoiding interference from adjacent tracks. Leveraging this technology can only increase storage capacities to a certain level, even when the most innovative platforms are used.

To expand capacities even further requires that the write head size be reduced, as well as the size of the magnetic grains that store bit information. Each grain within the media is a tiny magnet that must be aligned in either an up or down direction to perform a write operation, and helped by a magnetic field invoked from the write head.

The challenge is whether enough magnetic field can be generated by the smaller head in order to flip the magnets in one direction, overcoming the energy barrier required. If the storage media is made with low coercivity, a lower energy barrier is required to flip the magnets, however, the media grains become susceptible to thermal instability and the magnets can flip inadvertently, losing integrity of data.

Therefore, increasing disk capacity requires storage media that has a high enough energy barrier to overcome thermal instability, as well as a write head that provides an assist to lower the energy barrier while writing to disk. There are two magnetic recording technologies being developed to provide the energy-assist, either heat-assisted or microwave-assisted.

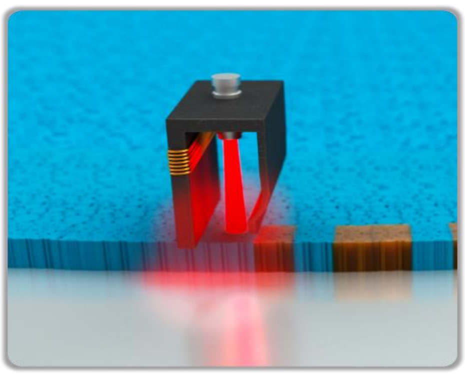
<u>Heat-Assisted Magnetic Recording (HAMR)</u>

Heat-assisted magnetic recording is a technology that has been anticipated for the past 10- to 15-years, with the promise of a HAMR-based drive. That hasn't happened, and for very good reason. In addition to significant costs, HAMR has engineering complexities and manufacturing challenges that need to be resolved before it can satisfy the reliability demands of today's data center.

HAMR technology is based on positioning a laser diode directly in front of the write head assembly, and very rapidly heating the high coercivity media that cannot be written to unless it is heated during the writing process. As the media cools down from the intense laser heat, the coercivity of the media increases, holding the bits in state, and making it difficult for the magnetization to inadvertently change.

Implementing a laser in every hard drive head assembly is expensive, driving up bill-of-materials (BOM) cost. But the real concern is that when high heat is induced to a small, narrow area, it causes serious reliability issues.

"The list of infrastructure and reliability challenges associated with HAMR are expected to take a longer time to resolve for a viable high-capacity HAMR drive."



In a HAMR drive, a laser diode heats the media to assist in magnetization

MAMR vs HAMR (continued)

The high temperatures caused by laser heating also prevent use of the cost-effective aluminum disk material that is generally used in today's capacity enterprise hard drives, and instead, requires the use of more expensive glass substrates.

HAMR drives also require development of new materials used to coat the media. Iron platinum is used for HAMR drives due to its coercivity and thermal properties. Most hard drives typically use cobalt platinum media, which has been enhanced over several generations and supported by a very efficient manufacturing process.

The list of infrastructure and reliability challenges associated with HAMR are expected to take a longer time to resolve for a viable high-capacity HAMR drive, and includes reliably heating a small, narrow spot with a laser diode, eliminating the material deposits from carbon vaporization that can cause residue on the head assembly, and reducing head/media wear-out that may also require host software changes.

HAMR Technology Assessment

It is Western Digital's assessment that HAMR drives will not be commercially viable in the near term. The company will continue to make appropriate investments in the technology, consistent with its product investment strategy, anticipating new innovations. At the same time, the company has chosen to introduce a more cost-effective, more reliable solution based on microwave-assisted magnetic recording (MAMR) technology.

Microwave-Assisted Magnetic Recording (MAMR)

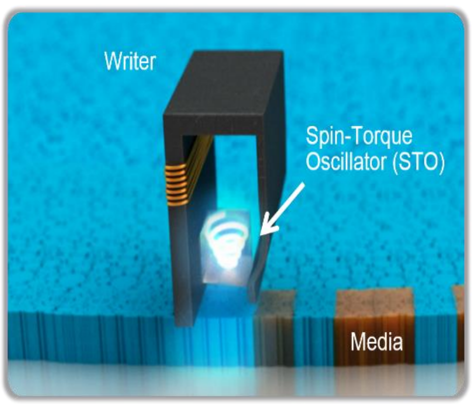
Western Digital has invested in and developed MAMR technology that uses a microwave field generated from a spin torque oscillator (STO). In this method, the STO located near the write pole of the head generates an electromagnetic field that allows data to be written to the perpendicular magnetic media at a lower magnetic field.

The magnetic grains on disk are similar to spinning gyroscopes that are stable in either an up or down direction in the absence of an external field. When a sufficient magnetic field is applied in the opposite direction of the current state of the magnets, the polarity flips in the direction of the applied field. Applying an additional field from the STO can flip the magnets more quickly, and at a lower magnetic field.

While the theory behind MAMR has been known in the industry, and in academia for many years, producing a manufacture-able head that demonstrates the MAMR effect, was elusive.

Western Digital

"Western Digital's MAMR technology is now ready for prime time, and provides a more cost-effective, more reliable solution, leveraging existing PMR competencies and infrastructure."



In a MAMR drive, the spin-torque oscillator (STO) generates a microwave field to provide assistance when magnetizing the grains prior to a write

MAMR vs HAMR (continued)

Western Digital's expertise in thin film magnetics, as well as the company's understanding of spin transport physics through its research work on spintronic devices (widely used as read-back sensors in read heads for the past twenty years), helped to advance MAMR technology.

The technical capabilities of the STO, coupled with the flexibility of the Damascene head-making process, enabled a complex head structure that embeds a tiny, yet effective STO, creating a breakthrough in head design, while achieving high capacity gains with high reliability.

From internal testing, MAMR technology is demonstrating higher gains than the best PMR heads currently available, and shows promising areal density growth. Lifetime reliability tests show that the median time to failure of MAMR heads is one hundred times better than HAMR heads. Additionally, reliability tests over a population of heads show that the write lifetime hours demonstrated for 99.99% of MAMR heads is several orders better than the write lifetime hours for 99.99% of HAMR heads.

As a result, Western Digital's MAMR technology is now ready for prime time, and provides a more cost-effective, more reliable solution, leveraging existing PMR competencies and infrastructure. Academic studies also show that MAMR also has the capability to extend areal density gains to 4Tb per square inch (in^2), and beyond, delivering significantly better gains than drives shipping today (SMR drive gains equal 1,300Gb/in^2, while PMR drive gains equal 1,100Gb/in^2).

Building on a solid technology foundation, Western Digital is investing in the advanced Damascene process, advanced micro actuation, and continued research in MAMR technology to extend track densities to over one million tracks per inch. The company has developed a technology roadmap, with multiple generations of capacity enterprise products that can address the exploding growth of data being generated.

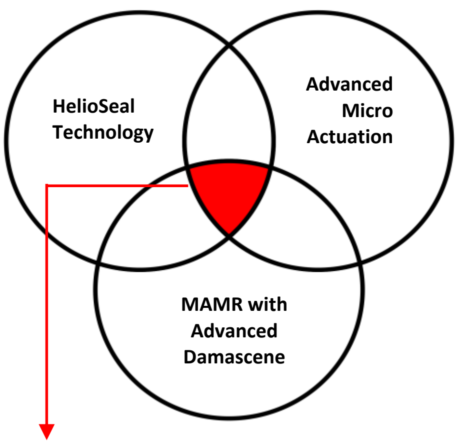
MAMR Technology Assessment

Given the company's MAMR innovations, Western Digital feels that the data storage industry can now benefit from increased capacities with MAMR technology and will productize MAMR-based drives for availability in 2019.

As MAMR is an energy-assisted magnetic recording technology that has been added to four generations of successful helium-sealed technology, Western Digital sees enough growth to productize MAMR sooner, considering the many engineering, manufacturing and reliability challenges HAMR will need to overcome in the next few years.

“Western Digital’s leading position in data storage technologies, solutions, and devices, for a wide variety of applications and work-loads, places them in a powerful position to define the future of data-centric compute and storage architectures.”

Western Digital’s Leading Position in Hard Drive Storage:



*Areal density gains
*Data center class reliability

Proven Execution

Western Digital has a long, successful heritage in hard drive innovation having developed the world’s first hard disk drive (in 1956), and since then, has introduced many breakthrough technologies. The company owns over 7,000 patents in hard drive technology and is the undisputed units shipped leader.

In 2013, the company introduced HelioSeal technology and the industry’s first helium-sealed HDDs (HGST branded), and has delivered four generations and over 20 million units shipped worldwide.

As the economics associated with capacity enterprise data storage is burgeoning for the next decade, Western Digital is committed to a new generation of capacity enterprise HDDs, driven by pioneering MAMR technology.

Western Digital is widely regarded for the unsurpassed quality and reliability of its HDD solutions over the years. Continuous improvements to each product generation, coupled with a commitment to excellence, will enable the company to achieve a 15% CAGR in enterprise hard drive storage capacity.

Summary

As the scale of data continues to increase through Big Data and Fast Data demands, and the diversity of application workloads expand, the world will need new data storage technologies and architectures that deliver both high-performance and increased capacities, with the right fit of value and capabilities. As such, flash-based SSDs and capacity enterprise HDDs will coexist far into the future.

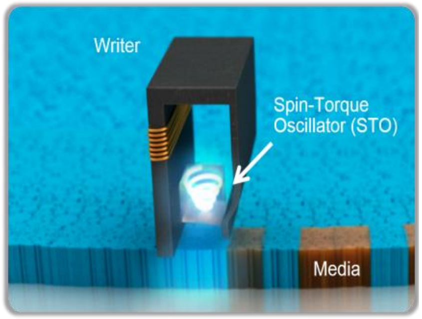
Western Digital’s leading position in data storage technologies, solutions, and devices, for a wide variety of applications and workloads, places them in a unique position to influence the future of data-centric compute and storage architectures. With the introduction of MAMR technology, the company is positioned to expand enterprise capacity over the next decade, and beyond.

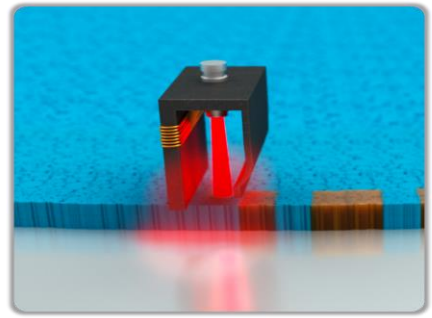
###

HDD Manufacturer	2016 Units Shipped	2016 Market Share
Western Digital (WDC)	175.51	41.4%
Seagate	155.01	36.6%
Toshiba	93.71	22.1%
Totals:	424.07	100.1%

Source: TrendFocus

Comparing MAMR vs HAMR:





	MAMR	HAMR
Cost	Similar to PMR technology	Added Costs (laser assembly, glass media, iron platinum coating)
Complexity	Leverages current PMR technologies	Requires new materials, re-engineering, and supply chain changes
Reliability	High reliability without inducing heat on the media	Serious reliability issues when heat is induced to a small, narrow area
Ecosystem Readiness	Plug-and-Play	Requires host software changes to manage wear-leveling
Manufacture-ability	MAMR drives in demonstration today – 1st product anticipated in 2019	No HAMR drives available today – Many cost and reliability challenges

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