2.5-inch HDD with World's Highest Areal Recording Density of 1 Tbit/in^2

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Toshiba has developed the MQ03ABB300 four-platter 2.5-inch hard disk drive (HDD) with a capacity of 3 Tbytes, the largest capacity in the market for HDDs with a 15 mm height form factor(*1). This was realized by achieving the world's highest areal recording density of 1 Tbit/in^2 (*2) and improving the formatting efficiency.

In order to attain such a high areal recording density, we developed the following technologies: a magnetic head equipped with dual heaters introduced for the first time in our 2.5-inch HDDs to reduce head-to-disk spacing, reduction of the disk magnetic cluster size to improve the signal-to-noise ratio (SNR), an advanced channel technology to enhance error correction capability, and dual-stage suspension (DSA) to improve the head positioning accuracy. Furthermore, the adoption of zone servo technology for the first time in our 2.5-inch HDDs to improve formatting efficiency also contributed to the achievement of large capacity.

1. Introduction

2.5-inch HDDs have been used mainly as data storage devices of notebook PCs. However, with the recent prevalence of tablets and cloud PCs, the demand for 2.5-inch HDDs for notebook PCs is declining. Meanwhile, the adoption of external 2.5-inch HDDs has been growing rapidly as they allow large movie and image files to be stored easily via a Universal Serial Bus (USB) and are convenient to carry around. There is a market need for external 2.5-inch HDDs with even higher capacity.

To meet this market demand, Toshiba has developed the MQ03ABB300 four-platter HDD that has a capacity of 3 Tbytes, the world's highest capacity for 2.5-inch HDDs, in a 15 mm height form factor. The world's highest areal recording density of 1 Tbit/in^2 and an improved formatting efficiency are the enablers for this 3 Tbyte HDD.

This report provides an overview of the MQ03ABB300 as well as the new technologies that have been developed to realize a 2.5-inch HDD with the world's highest capacity.

2. HDD overview

Table 1 shows the key specifications of the MQ03ABB300 2.5-inch external HDD.

Table 1. Main specifications of MQ03ABB300 2.5-inch HDD

Characteristic	Specification
Capacity	3 Tbytes
Number of platters	4
Number of magnetic heads	8
Linear density (average)	92.8 kbits/mm
Track density (average)	17 700 tracks/mm
Areal density (average)	1 641 Mbits/mm^2
Rotational speed	5 400 rpm
Buffer Size	16 MiB
Average seek time	12 ms
External dimensions	69.85 (W) × 100.0 (D) × 15.0 (H) mm
Weight	180 g (max)

MiB: mebibyte = 2^{20} bytes

The MQ03ABB300 contains four magnetic disks, or platters, in a 15-mm thick casing and has an average areal recording density of 1 641 Mbits/mm^2 (1.059 Tbits/in^2), approximately 1.42 times that of the previous model. This significant increase in areal recording density has been achieved by combining the following: our first dual-heater magnetic heads to reduce head-to-disk spacing, a reduction in magnetic cluster size to improve the SNR, an HDD read channel technology to increase the error correction capability, and DSA suspension to improve the head positioning head accuracy. Furthermore, our first adoption of zone servo technology has contributed to improved formatting efficiency and thus storage capacity.

(*1) As of January 2015 (as researched by Toshiba)
(*2) As of January 2015 for 2.5-inch HDDs (as researched by Toshiba)

3. Mechanism design

The newly developed HDD contains four platters and eight magnetic heads in a casing with a height of 15 mm (**Figure 1**). In order to achieve a high track density, a high-precision actuator is provided with DSA suspension that has piezoelectric elements in the vicinity of magnetic heads (**Figure 2**). Accompanying the use of dual heaters, the number of terminals on each magnetic head has been increased from eight to nine.

Owing to the use of DSA suspension, the servo system of the MQ03ABB300 provides better disturbance suppression characteristics than those of the previous 15 mm-thick MQ01ABB200 at frequencies below 2 kHz (**Figure 3**).

Due to the higher bandwidth, the MQ03ABB300 exhibits a positioning error approximately 40% less than that of the MQ01ABB200, making it possible to increase track density.

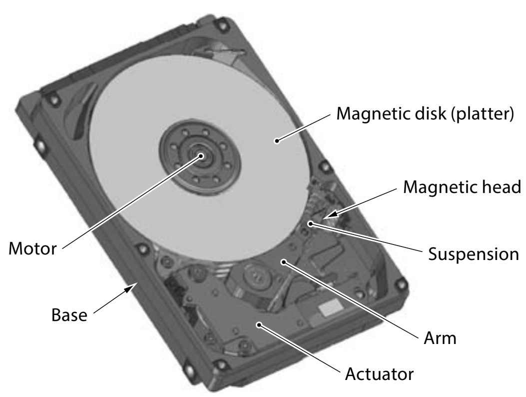


Figure 1. Internal structure of MQ03ABB300.
The magnetic disk, magnetic head, actuator, and suspension have been newly developed to achieve a high recording density.

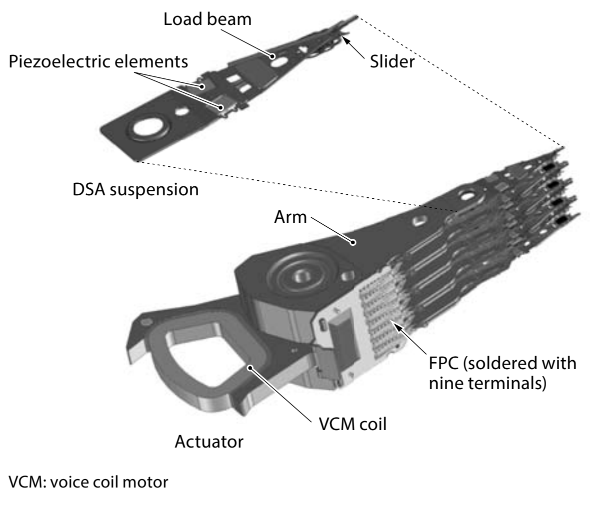


Figure 2. Newly developed actuator and DSA suspension.
A DSA suspension is used to increase the servo bandwidth, and a flexible printed circuit (FPC) is connected to dual heaters via nine terminals.

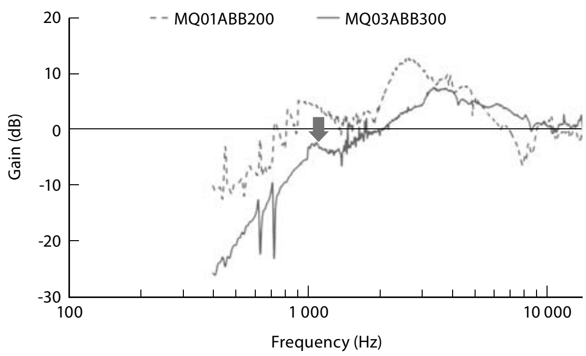


Figure 3. Comparison of disturbance suppression characteristics.
The MQ03ABB300 uses DSA suspension to provide better disturbance suppression characteristics than its predecessor, the MQ01ABB200, at frequencies below 2 kHz.

4. Improvement of recording density

The MQ03ABB300 has an average linear density of 92.8 kbits/mm in the track direction. Its data cylinders have a track density of 17,700 tracks/mm in the radial direction. The increases in linear and track densities combine to increase recording density.

In order to improve linear density, the head-to-disk spacing has been reduced by using a dual-heater technology, the SNR has been improved by reducing the magnetic cluster size of magnetic disks, and the error correction capability has been enhanced by using a read channel technology.

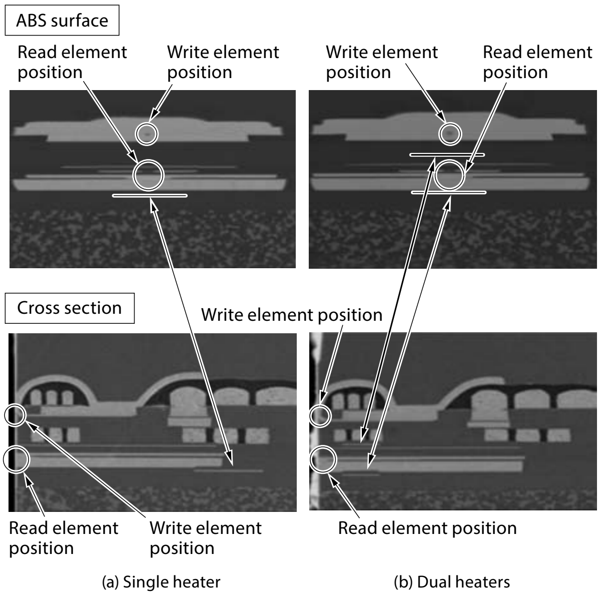
In order to increase track density, the write and read core widths of magnetic heads have been reduced, and the head positioning accuracy has been improved by using DSA suspension.

The reduction in the write core width causes a reduction in the write (overwrite) capability. To compensate for this impact, the head-to-disk spacing has been reduced, the write element structure of magnetic heads has been optimized, and the magnetic disk characteristics have been tuned according to the head characteristics. Furthermore, the MQ03ABB300 incorporates various technologies for optimizing data areas, track density and linear density of each magnetic head, with the aim of achieving the maximum possible capacity.

The following subsections describe the key technologies used in the MQ03ABB300 to achieve high recording density: head-to-disk spacing control using dual heaters and a reduction in the magnetic cluster size of magnetic disks.

4.1 Head-to-disk spacing control using dual heaters

The reduction in head-to-disk spacing has been achieved by the use of dynamic flying height (DFH) control, which dynamically adjusts the clearance between the magnetic head and the magnetic disk with



ABS: air bearing surface

Figure 4. Scanning electron microscope (SEM) images of magnetic head elements equipped with single and dual heaters.
The MQ03ABB300 uses a dual-heater structure in which separate DFH heaters are placed in the vicinity of the write and read elements. This makes it possible to maintain their flying heights at a constant altitude.

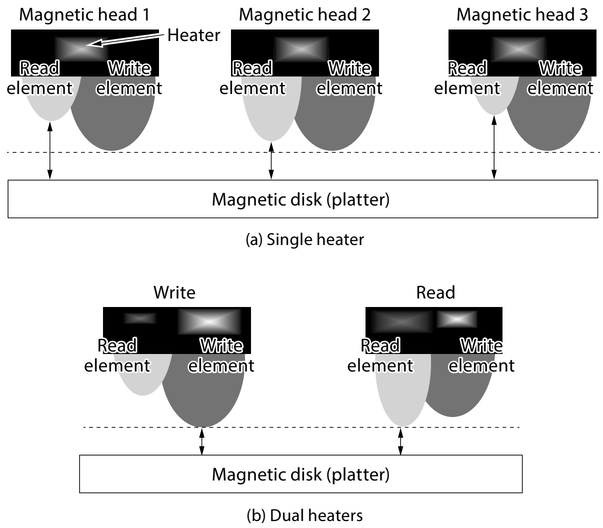


Figure 5. Comparison of protrusion shapes of write and read elements with single and dual heaters.
Whereas a single-heater structure cannot adjust flying height variations for the read element of each magnetic head, a dual-heater structure can control the flying heights of the write and read elements independently.

subnanometer precision. The DFH control method uses voltage-controlled heaters embedded in the magnetic head to thermally expand and protrude the head elements.

The MQ03ABB300 employs a dual-heater structure in which separate DFH heaters in the vicinity of the write and read elements control their flying heights independently (**Figure 4**).

With the conventional single-heater structure, the write element is positioned at an altitude closest to the magnetic disk even during reading. This makes it impossible to optimize the flying height during reading. Because of manufacturing variations, the write and read elements do not have constant heights (recesses) from the slider surface; thus the flying height of the read element cannot be kept constant owing to the effect of thermal expansion caused by ambient temperature changes.

In contrast, the MQ03ABB300 is designed to position the write and read elements at the lowest altitude during writing and reading respectively and to keep their flying heights constant. The use of dual heaters makes it possible for the MQ03ABB300 to optimally adjust the flying height separately during writing and reading (**Figure 5**).

Furthermore, the technology for dynamically keeping the flying height constant has been improved. For example, the DFH heater power resolution of the magnetic head preamplifier has been quadrupled compared to that of the previous model. As a result, the MQ03ABB300 has 60% less variations in the flying height, making it possible to realize low head-to-disk spacing.

4.2 Reduction in magnetic cluster size

As the recording density increases, the number of magnetic crystal grains per bit of storage decreases. To improve the SNR, magnetic transition characteristics at the bit boundary of magnetization reversal (switching) should be improved. To address this issue, we have reduced the size of magnetic clusters, the smallest unit that can be magnetically reversed (**Figure 6**), as well as switching field distribution.

Reducing magnetic cluster size tends to degrade magnetic cluster dispersion. Thus, our focus was on matching the characteristics of the magnetic head with those of the disk to reduce the degradation of magnetic cluster dispersion (**Figure 7**). For example, the write element design in the magnetic head has been optimized (e.g.,

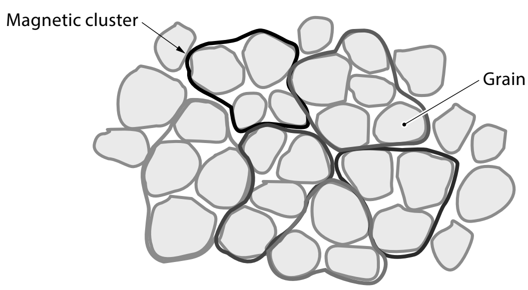


Figure 6. Schematic diagram of magnetic cluster.
A few grains comprise a magnetic cluster.

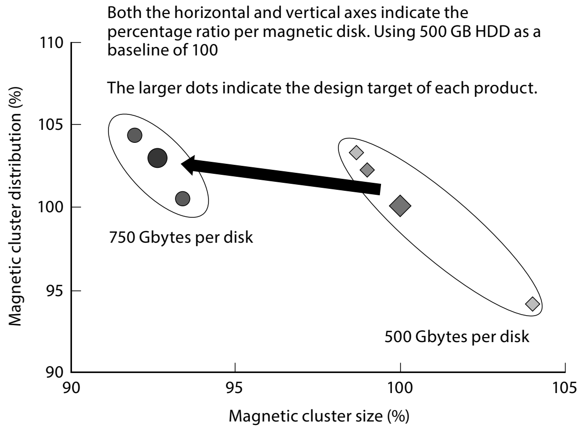


Figure 7. Relationship between magnetic cluster size and magnetic cluster dispersion.
The magnetic cluster size has been reduced without degrading magnetic cluster dispersion.

gap reduction). Since the reduction in magnetic cluster size, thermal fluctuation and write performance are characterized by a "trilemma" or a three-way dilemma, we paid special attention to the balance of these characteristics.

5. Improvement of formatting efficiency

5.1 Zone servo system

Figure 8 compares the servo patterns of the MQ03ABB300 and those of the previous model. The previous model has a constant servo pattern frequency from the outer to inner tracks of a disk. Therefore, the servo pattern frequency had to be determined based on the requirement of the inner tracks with higher linear density. As a result, middle to outer tracks had a higher SNR than was necessary. In contrast, the MQ03ABB300 is divided into three zones, each of which runs at a different servo pattern frequency, making it possible to reduce the total area occupied by servo patterns. This has contributed to a significant improvement of formatting efficiency.

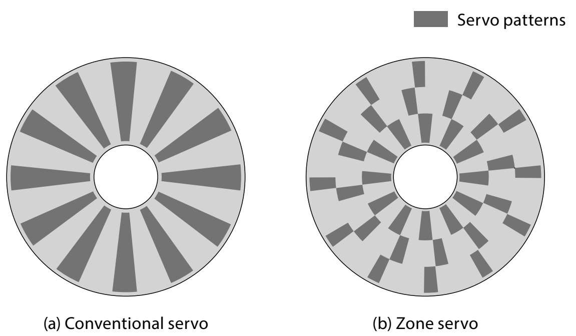


Figure 8. Comparison of servo patterns of conventional and zoned servos.
The zoned servo divides a disk into three servo zones to optimize the servo pattern frequency in order to reduce the area occupied by servo patterns.

Basically, the purpose of seek control is to move a head to a target track on a disk at high speed, based on the positional information obtained by demodulating servo patterns. However, servo patterns might not be detected owing to a difference in servo pattern frequency among the outer, middle, and inner zones of a disk. To address this issue, we have developed new routines for seek, read channel, and servo-gate control, achieving a seek error rate equivalent to that of the conventional servo patterns (with a single frequency).

5.2 Bidirectional servo writing

The direction in which servo patterns are written has been optimized. The conventional model writes servo patterns in one direction (backward from inner to outer tracks). This causes an SNR to decrease in the outer servo zone owing to the side-fringe effect caused by a skew of the write head. The MQ03ABB300 reduces the side-fringe effect by writing servo patterns to the inner and middle zones in the backward direction and to the outer zone in the forward direction (**Figure 9**). Consequently, the MQ03ABB300 provides servo patterns in the outer zone with an SNR 1.5 dB higher than that of the conventional model (**Figure 10**).

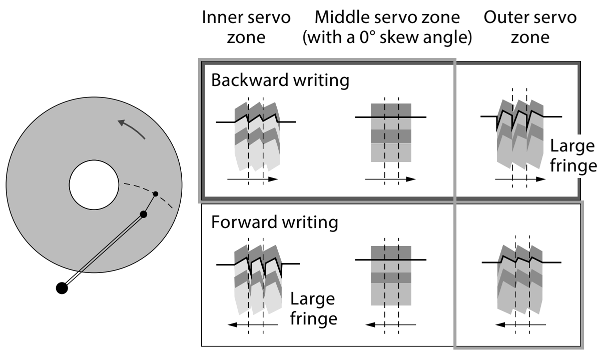


Figure 9. Differences in side fringe according to direction of servo pattern writing.
To reduce the side-fringe effect, the outer servo zone is written in the forward direction.

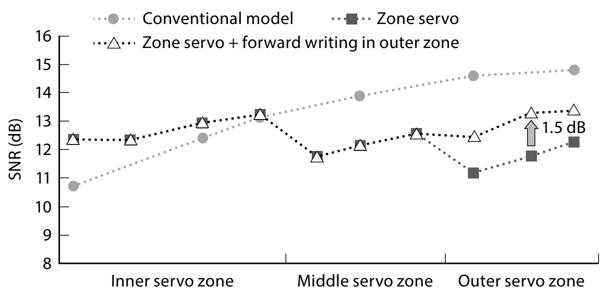


Figure 10. Improvement of SNR of servo pattern by forward writing at outer servo zones.
The SNR of servo patterns in the outer zone has been improved by 1.5 dB by writing them in the forward direction.

6. Conclusion

We have developed a four-platter 2.5-inch HDD with a capacity of 3 Tbytes, the largest capacity in the market for HDDs with a 15 mm height form factor. This was realized by achieving the world's highest areal recording density of 1 Tbit/in^2 and improving the formatting efficiency. Now that we have achieved an areal recording density of 1 Tbit/in^2 that is said to be the limit achievable with the current recording method, the density and capacity of HDDs will continue to increase in the years ahead.

Toshiba will continually work toward further increasing density and capacity to develop HDDs with industry-leading capacity and performance.

References

(1) Kusumoto, T. et al. 2011. "2.5-inch Hard Disk Drive with High Recording Density and High Shock Resistance (in Japanese)." *Toshiba Review* 66 (8): 36–39.

(2) Kurosawa, S. et al. 2014. "1 Tbyte Recording Capacity 2.5-inch HDD with 7 mm Height Form Factor for Mobile Notebook PCs (in Japanese)." *Toshiba Review* 69 (11): 46–49.

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Notes:

"-inch" means the form factor of HDDs or SSDs. It does not indicate drive's physical size.

This publication may include Toshiba's original estimation, and/or data based on Toshiba's evaluation.