Development And Application of Magnetic Storage Technology

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Abstract. Magnetic storage technology plays an important role in modern information storage and is the main way of modern information storage. The basic principle is to define the different magnetization states of the magnetic medium as "1" and "0" in the binary, and to realize the storage of information by changing the magnetization state of the magnetic medium. This paper summarizes the basic principle of magnetic storage technology, the characteristics of longitudinal magnetic recording and perpendicular magnetic recording, and their respective advantages. At the same time, this paper also studies the structure, advantages, and development trend of hard disk drives and magnetic random-access memory based on magnetic storage technology. For the frontier of magnetic memory technology, this paper focuses on the physical properties of magnetic Skyrmions and the possibility of magnetic Skyrmions in magnetic memory devices. For the memory using magnetic Skyrmions, topological Hall effect and magnetoresistive effect can be used to complete the writing and reading of information. Finally, this paper is expected to review the importance of magnetic storage technology.

Keywords: Magnetic storage; Magnetic recording; Skyrmion; Hard disk drive.

1. Introduction

Magnetism has played a vital role in the development of the whole world. China's early research on magnetism led to the invention of the compass, which provided a directional function for later sea navigation. For the study of magnetism, history is a long development process. In 1600, in his book titled *De Magnete*, William Gillbert noted that the positive and negative poles on the magnet appeared in pairs and were not independent of each other, and proposed the hypothesis that the Earth was a giant magnet [1]. In 1820, the Danish physicist Oersted discovered the magnetic effect of electric currents [2]. In the period that followed, the study of magnetism entered a period of deep understanding. At the beginning of the 19th century, the French scientist S. D. Poisson worked based on the theory of distance Poisson equation is established on the theory of electrostatic and magnetic potential [3]. Faraday's law of electromagnetic induction and Maxwell's equations laid the foundation of classical electromagnetism [1].

In the field of magnetic research, magnetic storage technology has received much attention. The principle of magnetic storage is to convert the information to be stored into a current signal through the control circuit, and then introduce the current into the magnetic head to produce a recording magnetization field. This magnetization field will magnetize the magnetic medium to achieve the purpose of information storage. In 1956, the invention of the IBM 350 RAMAC marked the dawn of the hard disk era [4]. In 1973, as the prototype of the modern hard disk, the Winchester hard disk was invented, its appearance increased the storage density of mechanical hard disks by more than 100 times [4]. In 2007, Hitachi adopted perpendicular storage technology in hard disks, which fully improved the reliability of hard disks [4]. In the current era, some cutting-edge magnetic storage technologies such as heat assisted magnetic recording (HAMR) and magnetic skyrmion have developed rapidly. The main purpose of these technologies is to increase storage density, improve read and write speed, and improve stability. These technologies are expected to revolutionize magnetic storage.

In this paper, the author will first introduce the principle of magnetic storage and the characteristics of two different magnetic recording methods, longitudinal magnetic recording, and perpendicular magnetic recording. Then, the author will start with the application of magnetic recording technology, focusing on the working principle, application field and development trend of hard disk drive (HDD) and magnetic random-access memory (MRAM). In the next part, the author will describe the characteristics of magnetic skyrmion in magnetic recording frontier technology and how magnetic skyrmion are applied in magnetic storage technology.

2. Magnetic Storage

2.1. The Principle of Magnetic Storage

Information works in binary form in computer, so information is also stored in binary form in magnetic memory. In the case of the HDDs, the magnetic coating of the hard disk is divided into many recording bits. A single recording bit region will have a positive or negative magnetization direction, which represents the 0 and 1 in binary. These record bits are combined to achieve data storage. In magnetic storage, there are two main ways to record data, the first is the longitudinal magnetic recording and the second is the perpendicular magnetic recording.

2.2. The Longitudinal Magnetic Recording

The main feature of longitudinal magnetic recording is that the magnetic induction direction is parallel to the direction of magnetic head movement, that is, the magnetic induction direction is horizontal. As shown in Fig. 1, the read/write system applies a magnetic field to the magnetic medium, the magnetization direction of each recording bit is aligned horizontally, and the data is recorded. Compared with perpendicular magnetic recording, longitudinal magnetic recording requires less magnetic field intensity in the process of data writing. What’s more, longitudinal magnetic recording is generally used in high-density magnetic recording. However, as the particle size of the hard disk continues to decrease, the sensitivity of the longitudinal magnetic recording to random thermal motion increases, resulting in the phenomenon of bit reversal [2]. In addition, due to the phenomenon of mutual exclusion of adjacent small magnets, which leads to the phenomenon of magnetization rotation. These will lead to the destruction of the stored data of the magnetic storage device, resulting in unstable storage phenomenon.

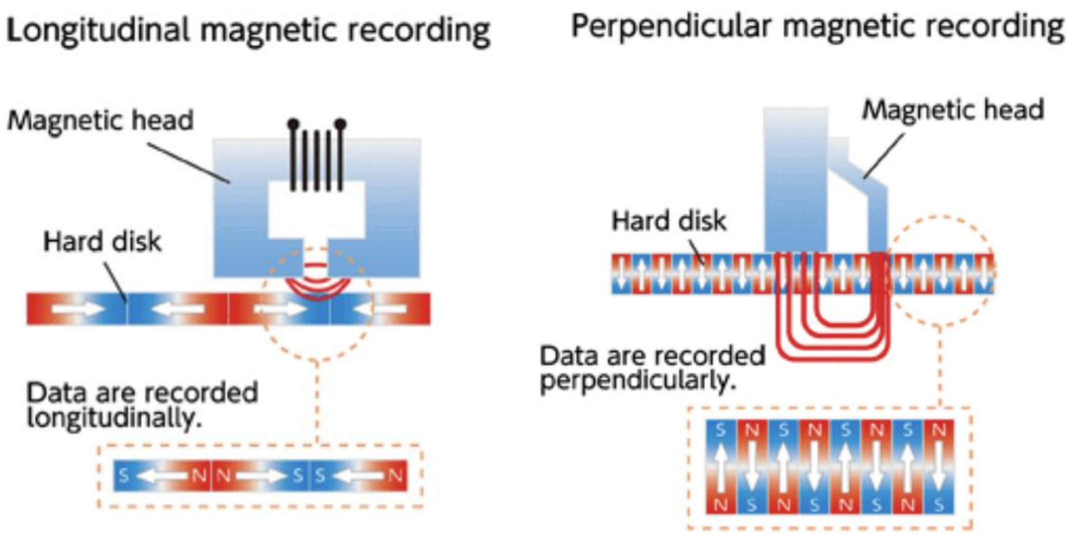

Fig. 1 Diagrams of (a) longitudinal and (b) perpendicular magnetic storage structures [2].

2.3. The Perpendicular Magnetic Recording

As shown in Fig.1, the main feature of perpendicular magnetic recording is that the magnetic induction direction is perpendicular to the direction of magnetic head movement. By comparing with the longitudinal magnetic recording mode, it is found that the longitudinal recording mode is stable at low recording density due to magnetostatic interaction, while the perpendicular recording mode is stable at high recording density [5]. In order to achieve perpendicular magnetic recording, a medium with perpendicular magnetic anisotropy is necessary. In the medium, the perpendicular magnetic recording technology uses Co-Cr as the perpendicular magnetizing film [5]. This is a Co-Cr material with both a high magnetization Ms and a high Hc sufficient to maintain high magnetization [5]. At present, perpendicular magnetic recording magnetic storage devices have become the main storage devices used by people [6].

2.4. The Work Way of Magnetic Storage Devices

In the process of information writing, a small electromagnet with a magnetic core is used as the writing magnetic head, and the data signal is converted into a current pulse by the circuit [7]. When the current is transmitted to the coil, the magnetic force line bypasses the magnetosphere and magnetizes the magnetic medium at the recording bit [7]. The 0 and 1 of the logical signals represent different current directions, to change the magnetization direction of the magnetic medium at each recording bit and record the information.

Because the magnetization direction of the two recording units is discontinuous, a transition region of magnetic field dispersion will be generated at the position of magnetization reverse, and the magnetic field lines in the transition region will radiate from the surface of the medium. When reading the information, the reading head detects the signal by using the giant magnetoresistance effect, which converts the magnetization direction of the recording bit into a current signal, so as to realize the data reading.

3. Applications of Magnetic Storage

3.1. Hard Disk Drive

The working principle of HDD is based on magnetic storage technology, which uses the control circuit to convert the stored data into electrical signals, and then drives the magnetic head to store the data in the form of magnetization on the disk; When the data is read, the magnetic signal stored on the disk is converted into an electrical signal by a control circuit, and finally restored to the original data. HDD has a large storage capacity, the basic capacity is usually in the prince section (TB) as a unit, this large-capacity storage capacity can meet the user's requirements for large amounts of data storage, and with the continuous progress of hard disk technology, the storage capacity potential of HDD is also constantly being tapped; Compared with other storage devices, HDDS are less expensive and difficult to manufacture, which makes HDDS cheaper. HDD data is stored directly on the physical disk, so when the data is damaged, through the relevant technology, the damaged data has a high possibility to be repaired.

As an excellent storage device, HDD has been widely used in computer, server, and other fields. In the computer, HDD provides a large amount of storage space for the user, which is used to save the operating system and software programs. HDD also plays an important role in the server and data field, HDD has the characteristics of high capacity and high stability, so that it has become an important part of the composition of the server and data center. Compared with other magnetic memory, HDD will improve performance and reduce cost as the direction of improvement development. On the one hand, HDD uses new materials, optimized read and writing heads, etc., to improve and stabilize the read and write speed and quality of HDD, and improve the storage density of data in HDD; On the other hand, the manufacturing process of HDD is further improved to reduce the manufacturing cost of HDD. In addition, HDD is also exploring new development directions in areas such as the Internet of Things and edge computing.

3.2. Magnetic Random Access Memory

As shown in the Fig. 2, the main structure of MRAM is a magnetic tunnel junction and an access transistor, and these two parts are important components of MRAM. The structure of the magnetic tunnel junction is a tunnel layer intermingled between two magnetic fixed layers and a free layer. Among them, the ferromagnetic layer is generally made of CoFeB material, and the tunneling layer is made of MgO material [8]. MTJ as a whole presents a "sandwich" structure [8]. The magnetization direction of the fixed layer is constant, while the magnetization direction of the free layer can be changed. This property produces two cases, when the direction of magnetization of the fixed layer and the free layer is the same, the tunnel reluctance of the magnetic junction is low. In contrast, the magnetic tunnel junction has a high magnetic resistance. Data is written by changing the magnetization direction of the free layer, or by passing an electric current through the junction to measure the magnetoresistance [8].

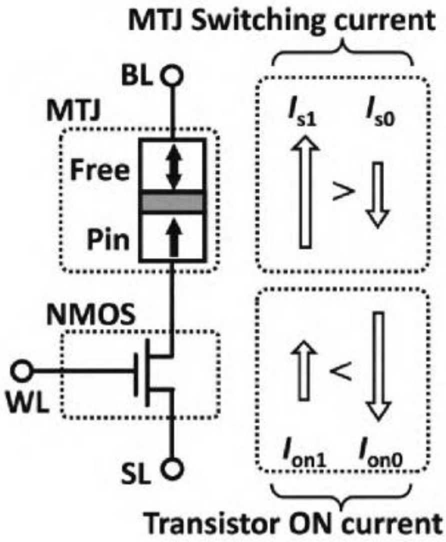

Fig. 2 Basic structure of the TIMC [8]

By comparing the data in the Table 1, this paper can draw a conclusion that compared with other memory devices, MRAM has the advantages of fast read and write speed, high durability and low power consumption. The memory unit of MRAM uses the magnetoresistive effect to access information, and the operation required in the writing process is only to flip the magnetic polarization direction of the free layer, and the movement of electrons and atoms is not involved in this process, so the power consumption is almost zero [8].

Table 1 Comparison of various memory devices [8]

Kind	Size	Read Delay	Write Delay	Durability Test	Quiescent Dissipation
HDD	N/A	5 ms	5 ms	$>10^{15}$	1 W
SLC Flash	4~6 F^2	25 μs	500 μs	10^4~10^5	0
DRAM	6~10 F^2	50 ns	50 ns	$>10^{15}$	Refresh dissipation
PCM	4~12 F^2	50 ns	500 ns	10^8~10^9	0
STT-MRAM	6~50 F^2	10 ns	50 ns	$>10^{11}$	0

As a memory with the advantages of non-volatile, high speed read and write and low power consumption, MRAM has a broad development prospect. At present, the mainstream development direction of MRAM is performance optimization and integration with other technologies. For example, in the future, MRAM may be integrated with new storage technologies such as PCM and ReRAM to form a more stable and efficient memory technology.

4. Magnetic Skymion

4.1. Magnteic Skyrmion

A Skyrmion is a topologically protected structure that can be characterized by a topological integer whose topological number does not change under continuous deformation in the field [9]. Defined in terms of topological numbers

$$Q = \frac{1}{4\pi} \iint q \, dx \, dy \,, \tag{1}$$

where $q = m \cdot \left(\frac{\partial m}{\partial x} \times \frac{\partial m}{\partial y} \right)$ is the topological density and m is the normalized magnetic moment. When the topological number is ± 1, the spin magnetic structure is considered to be magnetic skyrmion [9].

The magnetic Skyrmion is a magnetic structure that spins around the center, the spin at the center is down, and the spin at the edge is up, the center and the edge are antiparallel, and the magnetic moment in the middle of the transition region gradually turns from down to up. Therefore, Skyrmions are also a special kind of magnetic domain wall structure, see Fig. 3. In addition, like magnetic domain walls, Skyrmions are divided into Bloch type and Neel type according to the two different rotation modes of magnetic moments [10].

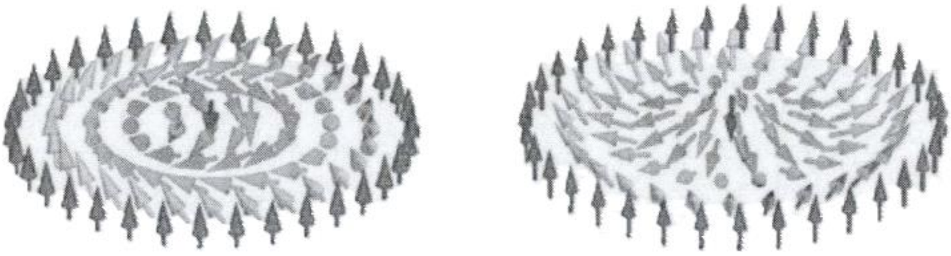

Fig. 3 The structure of Bloch type and Neel type magnetic skymion [10].

At present, compared with other magnetic structures, magnetic Skyrmions have great advantages in the use of magnetic ultra-high density storage units and logical computing units. For example, because the magnetic Skyrmion is a quasiparticle that can be driven and manipulated by a low-density current, a new generation of magnetic memory devices and logic computing devices can be built from the magnetic Skyrmion [11].

4.2. Development Prospect of Magnetic Skyrmions in Magnetic Storage

In order to solve the problem of the application of magnetic Scomingons in the field of magnetic storage, Parkin et al. proposed a model concept of "racetrack memory "[11]. In this racetrack memory idea, there are many magnetic domains on a nanostrip, and the anisotropy results in only two directions for the domains, different directions can represent the information being written, such as "1" pointing in the positive direction, and "0" in the opposite direction, and the domains are separated by the walls of the domains [11]. At the same time, because of spin transfer moment, a series of magnetic domains can be driven and regulated by the current, so that the magnetic information can be written and read. Track storage has strong anti-shock and anti-interference, which is conducive to the information storage of mobile devices [11]. In theory, when the spin polarization current is used to drive the domain wall, the speed can reach hundreds or even thousands of meters per second. The writing and reading of the data are realized by using topological Hall effect and magnetoresistive effect, which are two kinds of detection schemes of Skyrmions.

4.3. Topological Hall Effect and Magnetoresistive Effect

Skyrmion is a kind of non-coplanar spin structure. When the conduction electron passes through the Skyrmion, the spin of the electron is coupled with the local spin inside the Skyrmion, so that the spin direction of the electron changes back and forth, and finally the electron can obtain a Berry phase. If the coupling of the two is strong (adiabatic conditions), then the conduction electron's spin will always experience an effect perpendicular to the direction of motion, forcing it to be parallel to the local spin, and this effect is related to the topological number of Skyrmions, called a "topological force". From the point of view of Skyrmion, the non-coplanar magnetic moment arrangement generates an excited electromagnetic field, which causes the electron to drift laterally, forming a measurable Hall voltage, and finally realizing the generation of Skyrmion. The equivalent magnetic field also can be called theemergent magnetic field [9]. It can be expressed as

$$bz = \frac{hc}{4\pi} m \cdot (\partial xm \times \partial ym) \tag{2}$$

Compared with the ferromagnetic state, when there is a Skyrmion, the non-collinear spin arrangement will lead to a certain change in the electronic state. Secondly, the heavy metal substrate will produce a large spin-orbit interaction, coupling the local magnetic moment to the real space direction, and further adjusting the motion state of the electrons [11]. These two effects will eventually affect the tunneling conductance or resistance together, so if a current perpendicular to the surface of the film is injected into the readout area, the magnetoresistive effect can be used to detect the Skyrmion.

5. Conclusion

To summarize, the magnetic storage technology defines the different magnetization states of the magnetic medium as "1" and "0" in the binary and uses the magnetic head to change the magnetization state of the magnetic medium through the longitudinal magnetic storage technology or the perpendicular magnetic storage technology, to achieve the purpose of information storage. In the field of practical application, HDD has become an important part of the server as a magnetic memory device with high capacity and high stability. The MRAM device, which is composed of two magnetic fixed layers and one free layer, with the overall sandwich structure, has gradually become the main magnetic memory device with the advantages of fast reading and writing speed and low power consumption.

With the development of science and technology, there are now many new magnetic storage technologies, such as magnetic Skyrmions. Skyrmion is a kind of topological protection structure, which is characterized by topological integer, and its topological number does not change when it is continuously deformed in the field, so the magnetic Skyrmion has good stability. In the track memory model, topological Hall effect and magnetoresistive effect are used to write and read data, which are two detection schemes of Skyrmions. Therefore, the application of magnetic Skyrmions in magnetic storage technology has great possibilities. Reviewing the paper, the author finds that magnetic storage technology, as the main way of modern information storage, is in a period of change and development. In the future, the development trend of magnetic storage technology is to improve the storage density and read/write speed of magnetic storage devices. With the development of nanotechnology and new material technology, the storage density of magnetic storage devices will further increase, which means that more data can be recorded. The development of magnetic storage technology will have a profound and good impact on people's lives and provide data storage support for the development of other technical fields such as big data and artificial intelligence. In short, magnetic storage technology is a very promising technical field.

References

[1] Bihlmayer Gustav. Density Functional Theory for Magnetism and Magnetic Anisotropy. Handbook of Materials Modeling: Methods, Theory and Modeling, Springer International Publishing, 2018.

[2] Pandey Tribhuwan, David S. Parker. Magnetic Properties and Magnetocrystalline Anisotropy of Nd_2Fe_{17}, $Nd_2Fe_{17}X_3$, and Related Compounds. Scientific Reports, 2018, 8(1): 3601.

[3] Chen Haoqi. First-principles research on magnetic correlation problems of two-dimensional materials. University of Science and Technology of China, 2018.

[4] Deng Yue. Hard drive development and new technology. Modern industrial economy and information technology, 2012, 13(08): 72-74.

[5] Zhan Xinong. Exploring a new magnetic recording method -- Talk about vertical recording. Telemetry Technology, 1979, 5(01):14-23.

[6] Alsubaie Munirah, et al. First-Principles Study of the Enhanced Magnetic Anisotropy and Transition Temperature in a $CrSe_2$ Monolayer via Hydrogenation. ACS Applied Electronic Materials, 2022, 4(7): 3240–3245.

[7] Nie Xiangfu, Ma Li, Guo Chengxin et al. Magnetic recording materials and their measurement. Journal of Hebei Normal University, 2005, 33(05):473-476+480.

[8] Yao Jialun, Yang Yumeng, Chen Haoyu. Overview of magnetic random-access Memory for storage and computing. Journal of Functional Materials and Devices, 2019, 27(06):525-535.

[9] Yang Hongxin. A review on the research status of Magnetic Skyrmions. Journal of Sichuan Normal University (Natural Science Edition),2021, 44(03):285-306+282.

[10] Wu Han-Zhao. Synthetic magnetic Skyrmions. Nanjing University, 2017.

[11] Liang Xue, Zhao Li, Qiu Lei, et al. Track storage of magnetic Skyrmions. Journal of physics, 2018, 13: 368-390.