

Chapter 7

Ferroelectric Probe Storage Devices

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7.1 Introduction

An information storage device is a gadget that has a probe head and a medium, and uses them as means for recording (write) and retrieving (read) information (see Fig. 7.1).

As the world gets more and more connected and linked, the amount of information flow will drastically increase, which boosts the demand for storage devices. For example, people are using smartphones not only to make a phone call but also to take pictures, surf various web sites, watch movies, and write emails to name a few.

Then, why do we need to store more information in our gadgets? Is it not sufficient to use storage devices with current capacity for such gadgets? The answer to this question can be found by looking at the trends of necessary amount of information in four areas: display, medical, financial, and security information.

As the technology developed, the display device has evolved from black and white to color, and to 3D. It can be easily found that the amount of information needed to display 3D images is orders of magnitude larger than that for color images. For medical information, people are more interested in customized medication based on their own gene information and personal health history with all X-ray and MRI images included, which would need about 4 exabytes (EB) (4×10^9 GB) [1]. Another important trend can be found in financial sector, where people want to

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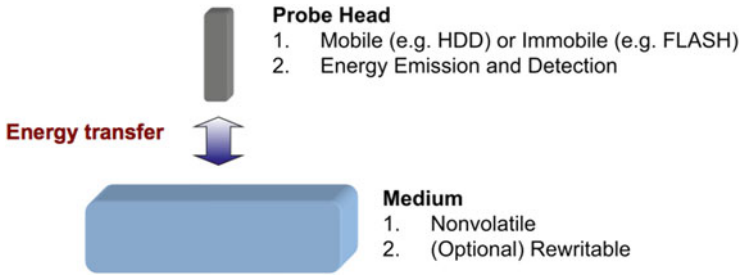


Fig. 7.1 Schematic of an information storage device, which mainly consists of a probe head and a medium

Table 7.1 Terminologies used for describing storage capacity in increasing order and their magnitudes

Storage capacity units	Equivalent storage capacity
1 TB (Terabyte)	1,000 GB (Gigabyte)
1 PB (Petabyte)	1,000 TB
1 EB (Exabyte)	1,000 PB
1 ZB (Zetabyte)	1,000 EB

have customized financial advice based on their personal banking and investment history. For safety and security reasons, more and more surveillance cameras are being installed in major cities with better resolution, which drastically increase the demand for storage capacity.

In parallel with the increasing demands to store more information in our gadgets, the available information increases exponentially as well. The information floating on the Internet is estimated to be more than 530 PB [1]. The telephone calls worldwide produce information about 17.3 EB per year. New information produced by print, film, magnetic, and optical storage media is roughly 5 EB per year (see Table 7.1 for the storage capacity units) [1].

The driving force to meet the ever-increasing demands for more information and supplies of such information has pushed the capacity of mobile HDD from 160 GB in 2007 to 1 TB in 2012 as shown in Fig. 7.2 [2].

7.2 Principle and History of Information Storage Devices

In order to develop new technology to meet the needs of the end users, one has to think about the right science that he or she can apply to realize the technology. Surprisingly one can find the common science and technology implemented in various mechanically addressable storage devices from the example of a note-taking process.

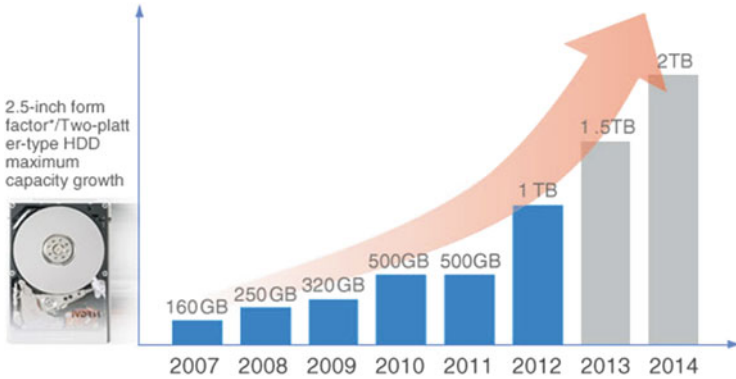


Fig. 7.2 Roadmap of mobile HDD embedded in laptops. Reprinted with permission from iVDR [2]

Fig. 7.3 Schematic of note-taking process, where the pen is the information writer and the human eye is the reader



As shown in Fig. 7.3, when we take a note during a lecture or a seminar, the pen becomes the writer and deposits inks on the notebook in the form of characters that encode information transmissible to people who use the same character set. The eyes become the reader and our brains decode the image of characters into meaningful words that form sentences conveying the message recorded on the notebook.

Two important activities involved in this note-taking process are (1) locating the place to write the characters and (2) finding the place where to read. This process is similar to servo and tracking of information in HDD or ODD. We use indentations or tabs to mark the first sentence of each paragraph and align each sentence vertically with the lines preformatted in our notebook (Y marker in Fig. 7.3), and use either the edge of the notebook or additional vertical line (X marker in Fig. 7.3) as

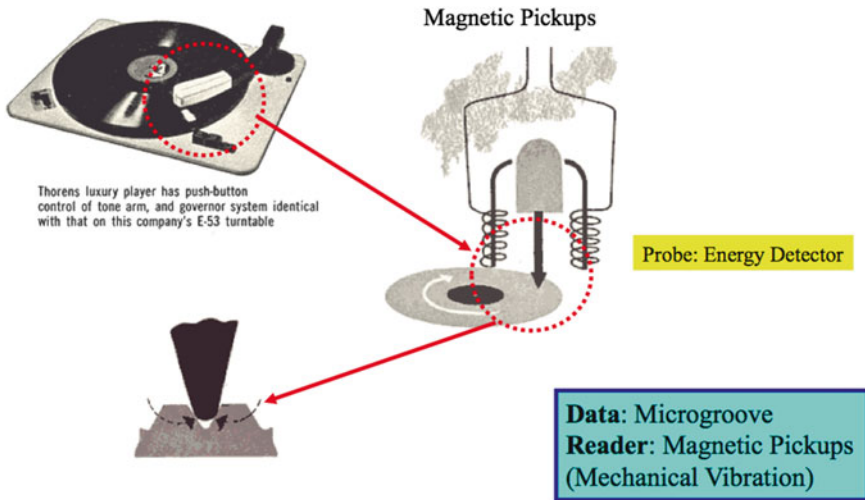


Fig. 7.4 Schematic diagram of phonograph, which has a magnetic pickup as the information reader. In the case of LP turntable, the microgroove acts as the information that contains the music, and the mechanical vibration of the pickup is detected by the inductive current

the reference to which we start our sentences. Likewise, when we want to find a specific sentence, we first identify the position by saying, e.g. the third line of the second paragraph. In this particular case, our eyes will quickly count the number of tabs of each paragraph from the top and locate the third line by counting again the number of lines from the top of the second paragraph.

We can learn more common science and technology embedded in mechanically addressable storage devices, or say probe storage devices by studying the prototypical turntables, optical disk drives, and hard disk drives. They all have similar mechanical structures when one considers the shape of media being circular, and the head moving in or close to the radial direction. The information is recorded sequentially along either one track or multiple tracks in the form of micron-size grooves for turntable, bits with different optical reflectivity using different phases for DVDs [3], and magnetic domains with different magnetization directions for HDDs. As such, the writing process would be imprinting the physical grooves for turntables (see Fig. 7.4), heating with laser source at different temperature and duration for DVDs (see Fig. 7.5) and applying focused magnetic fields with different polarity and duration for HDDs (see Fig. 7.6) whereas the reading process would be detecting the height of the grooves using magnetic transducers or piezoelectric transducers for turntables (see Fig. 7.4), detecting the intensity of reflected laser beam for DVDs (see Fig. 7.5) and measuring the current amount passing through magnetoresistance device which has different resistance depending on the direction of magnetic field emanating from the HDD media (see Fig. 7.6) [19, 20].

Moreover, the heads are located in the arm that has a balance mass on the opposite side of the pivot, which absorbs the lateral vibration and shock. Therefore, if one can conceive of a physical mechanism to write and read information using different

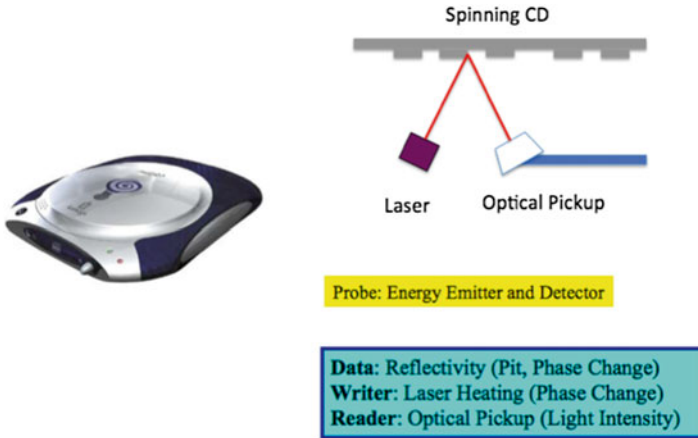


Fig. 7.5 Image of DVD player and schematic diagrams of the media and the optical pickup. The optical head has a laser source that heats the media locally to induce a phase change, which can be detected by the laser reflected from the bit [3]

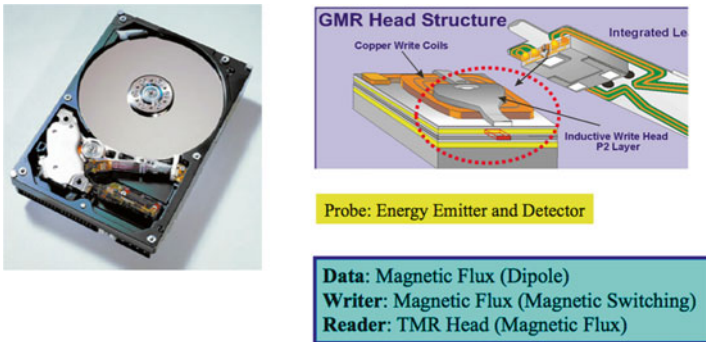


Fig. 7.6 Image of a hard disk drive (HDD) along with a schematic of a HDD head composed of inductive copper write coils and giant magnetoresistance (GMR) reader. Courtesy of International Business Machines Corporation, ©2014 International Business Machines Corporation

transduction scheme, e.g. writing with electric field and reading back with a resistance change induced by electric field, then one can invent a new recording system based on the mechanically addressable framework.

7.3 Understanding Key Processes of Information Storage

In order to come up with a novel idea to increase the density and speed of information storage, one has to think about the key processes that govern the writing and reading of information in the device. Here we present three distinct processes that

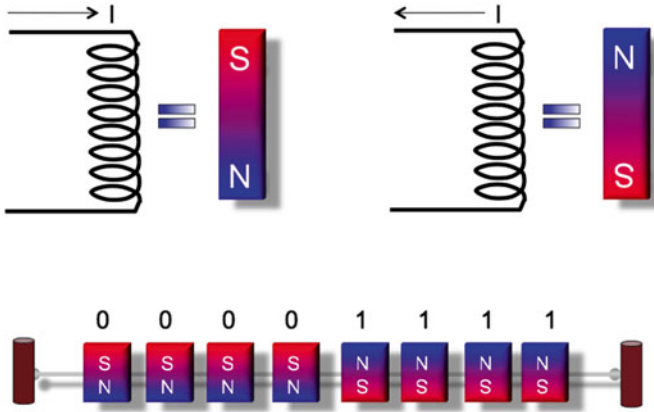


Fig. 7.7 Schematic drawings of writer coils with current flowing from top to bottom (*left upper*) and current flowing from bottom to top (*right upper*)

are important to construct an information storage device. The first process is designing the writer with a transduction mechanism from electrical energy into magnetic energy in the case of HDD. Figure 7.7 shows the schematic representation of induction coils embedded in the HDD head that are equivalent of permanent magnets with opposite direction depending on the flow of current through the coil. The media can be envisioned as a row of magnets threaded through a string that hold those small magnets, which store the information bit by bit, and as the HDD head travel above each bit and exert magnetic field, the bit either flip or stay depending on the polarity of the head.

From Fig. 7.7, one can immediately understand the limitation of writing with induction coil. The speed of writing depends on how fast you can flow the current through the coil, and any damping in the circuit will impede the process. Moreover, any heat loss due to the joule heating of the coil will increase the power consumption of the magnetic write head. Therefore, spin or charge injection could be a faster write mechanism for future storage devices [18].

The second process is the amplification process of the read signal. As depicted in Fig. 7.8, we can understand the process with a cartoon of water tank equipped with a gate valve that opens upon the impingement of raindrops collected by a cup connected to the valve. People usually get confused about the concept of amplification, as it seems to violate the law of energy conservation. How can one design a device where the output energy is bigger than the input energy? In fact, we cannot violate the law of energy conservation, and we can only amplify signals using two independent stream of energy (or material) flow that are connected via three terminals called source, gate, and drain. As depicted in Fig. 7.8, the amount of water contained in one raindrop is very small, therefore the input signal is very small. However, as the signal defined by the change of flow can be manipulated by a lever connected to a gate valve that regulates the water flow from the tank, the signal can be amplified by orders of magnitude as shown in the output signal plot in Fig. 7.8.

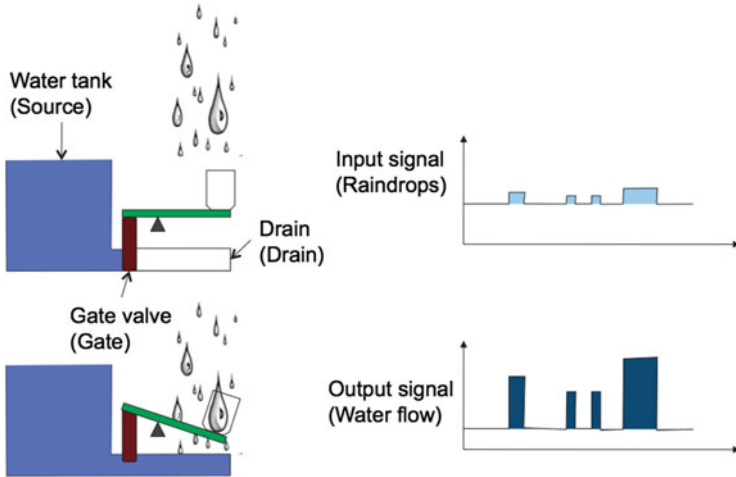


Fig. 7.8 Schematic diagrams of signal amplification mechanism. The tank filled with water acts as a source of signal, and the gate valve connected to the cup via a lever supported by a pivot acts as the gate for the signal. Output signal in terms of water flow through the channel will replicate the raindrops collected in the cup with much amplified strength

Therefore, it is important to invent a mechanism where the small field emanating from the information bit can trigger a large flow of current through a gate opened and closed by the field. One such a mechanism is magnetoresistance, where the stray magnetic field from the magnetic domain can either increase or decrease the resistance between the source and drain terminals of the giant or tunneling magnetoresistance devices as depicted in Fig. 7.9. The mechanism shown in Fig. 7.9 illustrates an example where the magnetic force is converted to mechanical force acting on the gate of the water tank. However, in reality, it is the magnetic force acting on the spins of the gate that increases or decreases the resistance of electrons with specific directions that flow through the tunnel junctions.

The last but not the least key component of information storage devices is the retention properties of written information. If the recorded data is not stable against environment, then the consumers cannot reliably use the device. Therefore, one has to make sure that each information bit has a proper barrier against flipping to the other state by thermal energy. Figure 7.10 depicts this idea by putting a fence or an activation barrier in the vicinity of the written information. One immediately sees a conflict here. If one wants to write the information easily, the fence should be low whereas if one wants to keep them stable against external perturbation, the fence should be high.

People have come up with an idea of raising the fence and increasing the writing energy. One way to accomplish this is to use both magnetic and heat energies when writing the bits, which is called heat-assisted magnetic recording (HAMR). However, this combined usage of two different energy sources complicates the device design. It should be noted that three major HDD companies have developed

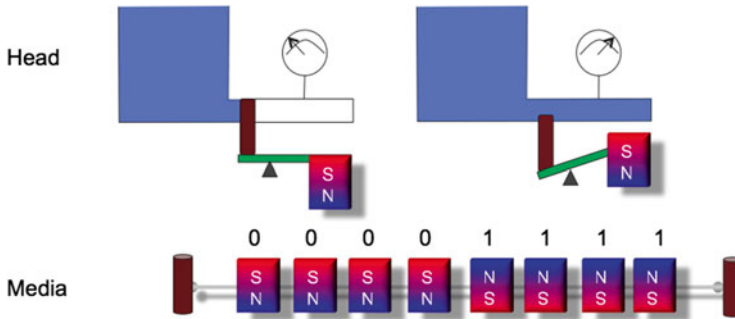


Fig. 7.9 Schematic diagram of reading process in hard disk drives where the polarity of dipole moments encoded as information bits can either open or close the gate valves to amplify the read signals

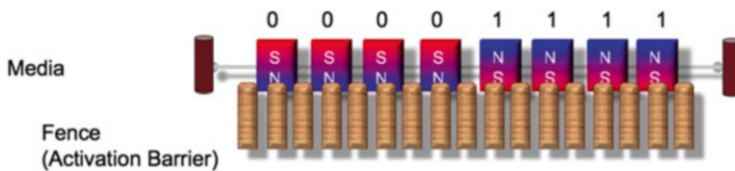


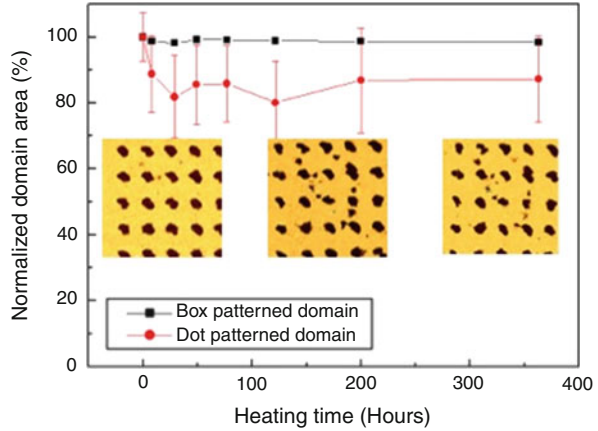
Fig. 7.10 Schematic diagram of written information bits with an activation barrier that keep the bits stable against thermal energy

HAMR technology that can be implemented in 2016 [4, 5]. Others have come up with the patterned media where they can increase the signal to noise ratio by increasing the change between the information bits [6]. However, mass production of regularly aligned nanoscale bits is a big challenge in the industry.

7.4 Ferroelectric Materials as Storage Media

Fong et al. at Argonne National Laboratory have published a seminal work on the size limit of periodic stripe domains in PbTiO_3 thin films grown epitaxially on SrTiO_3 substrates [7]. They have found that down to three unit cells, one can sustain ferroelectricity at room temperature. As the domain size scales with the thickness of the film, this would mean that one can write information within a diameter less than a few nanometers leading to potential bit density larger than 10 terabits/in.² [8]. Regarding the thermal stability of written bits, Woo et al. have found that fully penetrated domains can retain its state [9], and Kim et al. have shown that so written bits can withstand the thermal energy at 200 °C for over 350 h as shown in Fig. 7.11, which translates into more than 10 years of retention even at 85 °C based on the assumption of thermally activated process with activation barrier of about 1 eV [10, 21].

Fig. 7.11 Normalized area of written information (*black dots*) on ferroelectric thin films as a function of elapsed time at 200 °C. The sample was imaged using piezoresponse force microscopy (PFM) at each time



Another issue that should be identified is the uniformity in the size of bits written under the same condition. It has been known for a long time that the grain boundary interacts strongly with domain boundaries to influence the size of the domain written by the electric field from the probe head. In order to minimize such fluctuations, Kim et al. have explored the relationship between the grain size and the domain size and its fluctuation as shown in Fig. 7.12 [11]. They found that reducing the grain size, which is the same approach taken in the HDD industry for ferromagnetic media, will lead to higher uniformity in the bit size written under the same voltage magnitude and duration.

Therefore, so-called nano-grain ferroelectric media were initiated and developed by Buehlmann et al., where he and his colleagues found that TiO_2 thin films can be deposited to thickness below 10 nm in a continuous form, and by converting the film to PbTiO_3 through gas phase reaction with PbO , they could obtain ferroelectric media with grain size below 5 nm as shown in Fig. 7.13 [12–14].

7.5 Ferroelectric Hard Disk Drive

One of the biggest challenges of ferroelectric probe storage device based on micro-electromechanical system (MEMS) is the wear of the probe [22]. As can be seen in Fig. 7.14a, the wear volume depends on the load we apply to the tip and the wear coefficient between the tip and the ferroelectric media among other factors. Figure 7.14b shows the scanning electron microscopy (SEM) images of the resistive tip before and after 10 mm sliding in contact mode with load of 17 nN and in tapping mode. One can clearly see the wear of the tip that leads to a significant change in the radius of the tip when operating in contact mode whereas such a wear is minimized when the tip is not in direct contact with the media surface.

As such Hong et al. developed a concept of ferroelectric hard disk drive based on the resistive probe developed before [15], which utilizes the design of air-bearing

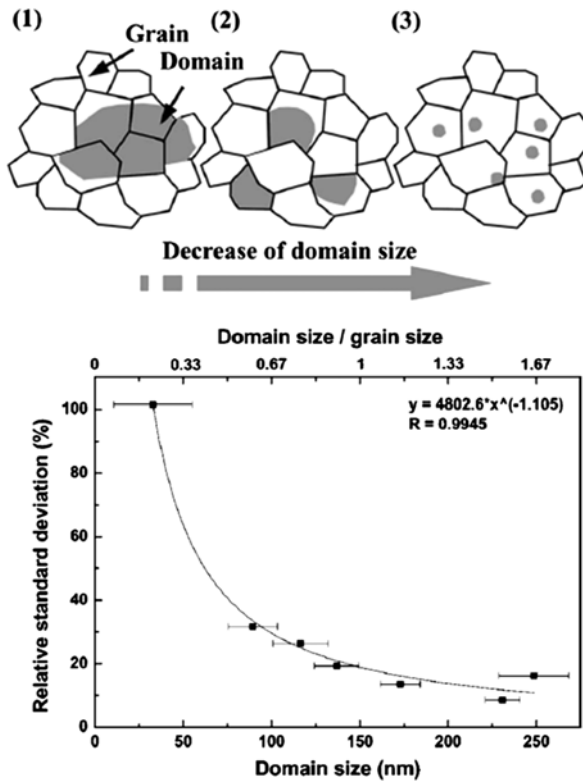


Fig. 7.12 Schematic diagram of overlapped images of written domains and grain structure in polycrystalline ferroelectric media. The grain boundary interacts with the domain to increase the standard deviation of the size of the written domains as depicted in the graph of relative standard deviation of domain size vs. domain size/grain size (or domain size). Reproduced with permission from Appl. Phys. Lett. [11]. Copyright 2006, AIP Publishing LLC

slider to maintain an air-gap of about 8 nm between the head and the media. In order to realize this concept, there are three imminent challenges that need to be addressed. Firstly, one should design a method to write ferroelectric domains even when there is a significant voltage drop across the air-gap. Secondly, the slider materials of AITC used for magnetic HDD should be changed into Si to embed field effect transistor as the information reader. Thirdly, one should develop ferroelectric media based on a HDD platter in a doughnut shape (Fig. 7.15).

Hong et al. combined the front-end process of fabricating the resistive channel and conducting writer on a silicon wafer using a standard nanofabrication process and the assembly of sliders in a standard HDD head fabrication process as shown in Fig. 7.16 [15]. One can clearly see the boundary in the center region of the top-view optical microscopy image of the slider, which was created by the wafer bonding process.

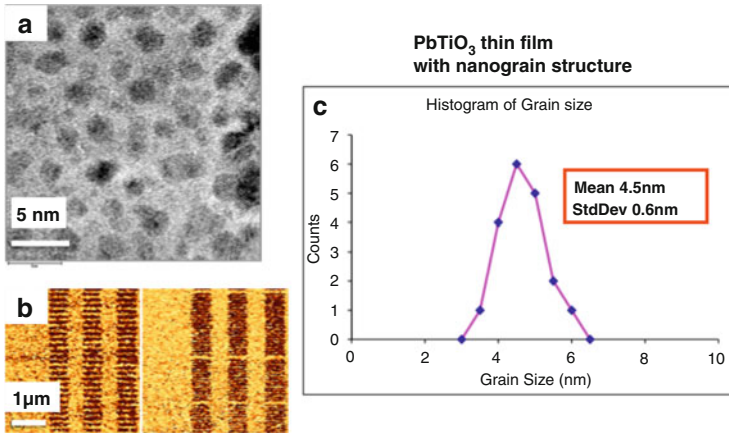


Fig. 7.13 (a) Transmission electron microscopy (TEM) image of PbTiO₃ thin film nanograin media, and (b) PFM phase images of written domains with line spacing of (left) 75 nm and (right) 38 nm. The pattern was written at voltages of ±3 V. (c) Histogram of the grain size measured from (a)

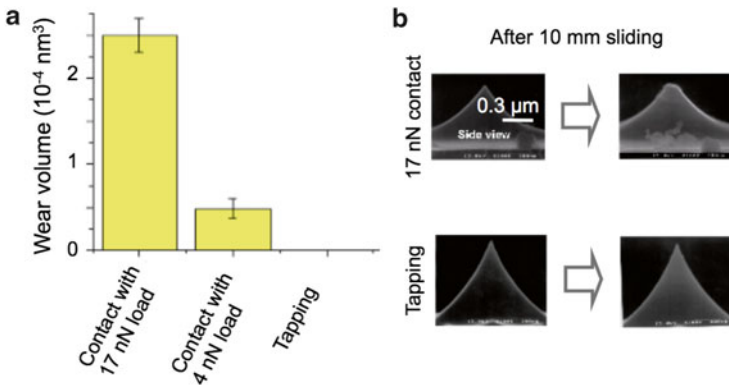


Fig. 7.14 (a) Plot of wear volume when operating at contact mode with load of 17 nN and 4 nN and tapping mode. (b) Scanning electron microscopy (SEM) images of the resistive tip after 10 mm sliding in contact mode with load of 17 nN and in tapping mode

The slider showed no debris attached to it after the flying test as seen in the optical microscope image. The acoustic sensor detected no sound, which indicates that our newly developed slider could fly above the media rotating at 7,200 rpm. With our fabrication process, we could address the challenges of fabricating the head using silicon instead of AlTiC.

The first and third challenges we discussed were addressed by conducting a model experiment using atomic force microscopy as well as performing the prototype experiment using the HDD head and ferroelectric media, which was polished to have less than 0.5 nm roughness using chemical–mechanical polishing (CMP)

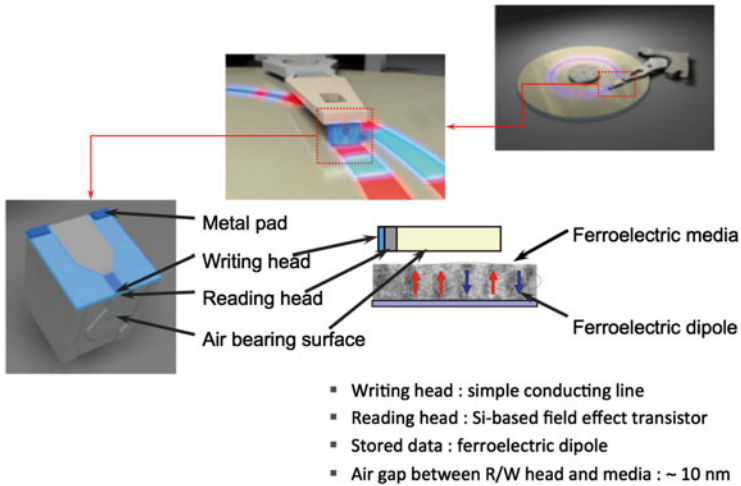


Fig. 7.15 Schematic diagrams of ferroelectric hard disk drive (FE-HDD). The head consists of a metal pad as the writer and a resistive channel as the reader. The air-gap between the head and media is about 8–10 nm, which is sustained by the airflow under the air-bearing surface. The media is ferroelectric thin film deposited on a silicon wafer diced to fit the HDD platform

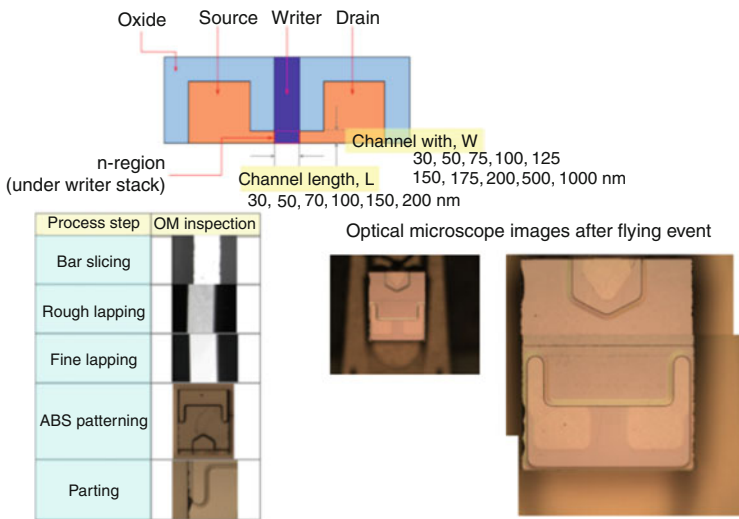
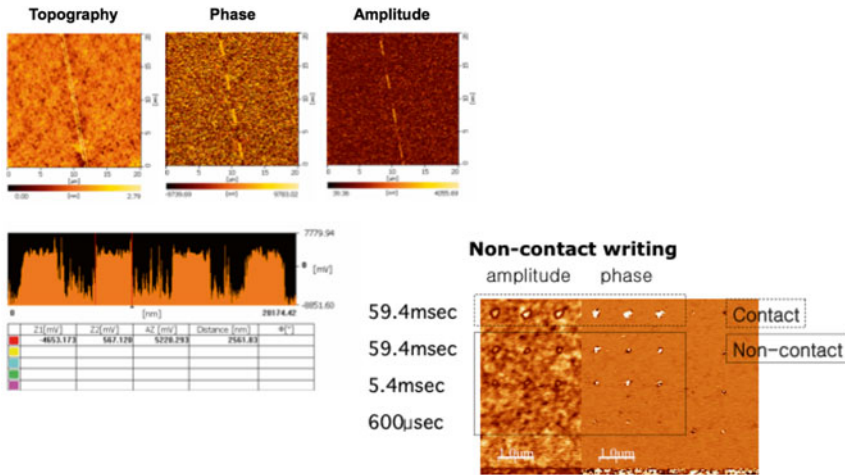


Fig. 7.16 Schematic diagram of the front view of FE-HDD head (top) and the processing sequence of head assembly (left bottom). Optical microscopy image of bottom view of FE-HDD head showing the air bearing surface (right bottom)



The size of switched domains is smaller for non-contact mode than contact mode.

Fig. 7.17 Topography, and PFM phase and amplitude images of a written track using a HDD head with bias voltage pulses of +10 and -10 V. Line profile along the track clearly shows the written ferroelectric domains. A comparative study using PFM shows that the bits formed in non-contact mode are smaller in size when compared to those formed in contact mode

process (see Fig. 7.17). We used laser-dicing method to make a hole in the center of the ferroelectric media.

We confirmed that the HDD head could be used as a writer through which we apply bias voltage pulses of opposite polarities (+10 and -10 V) and write alternating ferroelectric domain patterns without damage to the surface of ferroelectric media as shown in Fig. 7.17. Furthermore, we compared the bit size of ferroelectric domains written by a biased AFM tip using the same duration of 59.4 ms using contact and non-contact tapping modes. As evident in the PFM phase images, the bit size is slightly smaller when written in non-contact mode than that written in contact mode.

Using PFM and Kelvin probe force microscopy (KPFM), Kim et al. found that the writing process consists of charge injection through the air-gap and polarization switching induced by the electric field exerted by the accumulated charges as shown in Fig. 7.18 [16]. This finding can explain the reason why we could write the domains even though we have an air-gap of 10 nm between the head and the media. The air-gap acts as tunneling barrier where the charges can flow as in the case of alumina capped ferroelectric thin films [17].

7.6 Conclusion

We have reviewed briefly the history of probe storage devices consisting of a probe and a medium, where the probe emits energy to the medium to write and read information and the medium store the information. The needs for ever-increasing

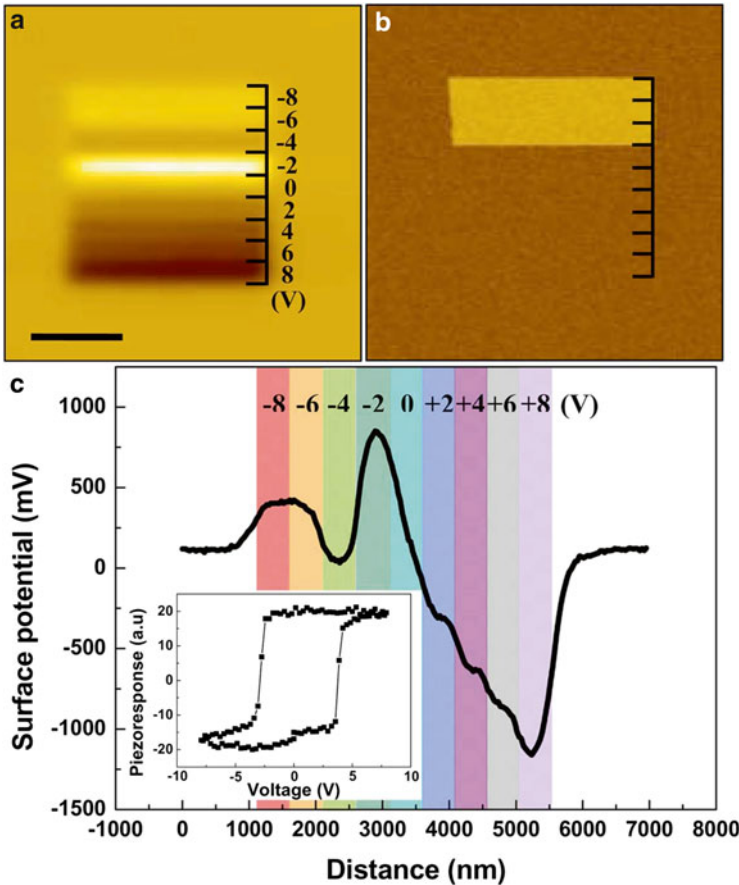


Fig. 7.18 (a) KPFM surface potential distribution and (b) PFM phase image of the area scanned with the applied voltage biases from -8 to 8 V with a 2 V step (*from top to bottom*) to the bottom electrode. The black scale bar presents $2\ \mu\text{m}$. (c) Surface potential line profile obtained from (a). The *inset* shows piezoresponse hysteresis loop of PTO thin films. Reproduced with permission from Appl. Phys. Lett. [16]. Copyright 2009, AIP Publishing LLC

information storage density in the mobile gadgets have driven the research and development of probe storage devices to find read/write mechanism that can scale down to nanometer scale other than existing HDDs and ODDs as they are approaching their storage density limits. We proposed the ferroelectric materials as one of the candidates for media with very high information storage density, as the ferroelectric domain could be as small as a few unit cells or $1.2\ \text{nm}$ in size. We showed that the writer is a simple conductor and the reader can be designed in the form of field effect transistors [23]. We envision that well-established hard disk drive system or newly developed micro-electromechanical system (MEMS) can be the candidates for realizing the ferroelectric probe storage device.

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