Research trends in magnetic nanowires

At NHK Science & Technology Research Laboratories (STRL), we are researching and developing sequential memory based on magnetic nanowires for video recording. Our aim is to use this technology in compact very high-performance cameras capable of extremely high definition and frame rates. In a magnetic nanowire produced using semiconductor fabrication technology, it is possible for information to be carried by magnetic domains that can be moved at high speed by applying a current along the length of the wire. We expect that this characteristic can be exploited to make lightweight recording devices that are more compact and faster than today’s devices. Also, such devices should be very reliable since there are no mechanical moving parts. This report discusses the basic principles of this technology, including how magnetic domains can be made to move in magnetic nanowires by applying a current and introduces the R&D trends of recording devices based on magnetic nanowires.

1. Introduction

To make a portable compact camera, it is essential for it to have a compact and lightweight storage device. Moreover, video technology continues to progress as far as the definition (i.e., higher spatial resolution) and, more recently, frame rate (i.e., higher temporal resolution) go, and this progress is generating a demand for storage devices with greater recording capacity and that can record video with higher definitions and frame rates. Current recording devices include magnetic tape, hard disk drives, and optical disks, but in the future these devices will become impractical for the applications we envision. In particular, we are developing a 33-megapixel hand-held Super Hi-Vision (SHV) video camera with a frame rate of 120 Hz that has an extremely high data rate (144 Gbps) that cannot be recorded with slower magnetic tape, hard disk drives, or optical disks unless dozens or even hundreds of such devices are operated in parallel. Reliability is another problem with devices that have moving parts; such extreme operating conditions will rapidly degrade them. At present, the only recording device that could be used by this camera is a non-volatile semiconductor memory such as an SSD (solid-state drive), but even so, today’s semiconductor memory and its associated equipment are still not fast enough to record Super Hi-Vision.

At STRL, we are engaged in the research and development of new magnetic recording devices that use microscopic structures called magnetic nanowires. Recording devices that use semiconductor memory operate faster than magnetic recording devices such as hard disk drives that have mechanical moving parts, and in principle, the time needed for them to record one data bit is approximately 1 ns. On the other hand, the ultimate recording time of magnetic recording with no mechanical moving parts is in principle from a few

![Figure 1: Basic operating principles of semiconductor memory and magnetic recording](image-url)
dozen picoseconds to 100 ps. This means that in principle magnetic recording should be substantially faster than SSD's. As shown in Fig. 1, in a semiconductor memory, the electrons in a memory cell are physically moved, and its principle of recording information is based on the presence or absence of electrons. On the other hand, in magnetic recording, the spin direction of a magnet's constituent electrons is changed in situ, so information is recorded by changing the orientation of the magnet's N and S poles. Since there is no need for electrons to be moved physically, essential magnetic recording is faster than SSD recording. Moreover, since a magnetic nanowire uses high-speed magnetic recording, it is akin to extracting a data track from a hard disk and stretching it out into a straight line. The operating speed of a hard disk drive is slow because the disk has to be rotated to record and play back information mechanically. On the other hand, a magnetic nanowire works by passing a current along its length instead of making it move mechanically. This current is used to record and play back information as the magnetic domains successively travel through the magnetic nanowire, allowing the device to operate at high speed. A magnetic nanowire has no mechanically moving parts, and thus it should be able to operate at high speed and with high reliability.

In this article, we will discuss the structure of magnetic nanowires and the principle of magnetic domain motion by the application of an electric current. We also describe the trend of R&D on recording devices based on magnetic nanowires.

### 2. Magnetic nanowires

#### 2.1 Magnetic materials and magnetic domains

A magnetic material is a material that is attracted by magnets, and it is divided into regions, called magnetic domains, with uniform magnetic moments. As shown in Fig. 2(a), when there is no external magnetic field, for example, each magnetic domain constitutes a closed loop and the magnetic forces cancel each other out so that magnetic poles (N or S) do not form. On the other hand, when an external field is applied to the magnetic material and its strength is increased, the boundaries between these domains move, or migrate, as shown in Figs. 2(b) and (c). The area of the domains that are magnetized in the same direction as the applied magnetic field increase until finally the material consists entirely of domains magnetized in this direction. In this state, the magnetic material is said to be magnetized. Magnetic materials have a very wide range of application in engineering, but in each case, the structure of the domains inside the magnetic material is controlled by an external magnetic field or electric current.

#### 2.2 Magnetic nanowires

When a magnetic material is made narrower, it exhibits magnetic shape anisotropy as shown in Fig. 3, \(^\text{1}\). A magnetic bias that occurs depending on the shape and dimensions of a magnetic material, whereby it tends to become strongly magnetized in specific directions.

\[^{1}\text{A vector quantity that represents a magnet's strength and orientation}\]

\[^{2}\text{A magnetic bias that occurs depending on the shape and dimensions of a magnetic material, whereby it tends to become strongly magnetized in specific directions.}\]
where magnetic poles appear at both ends of the material even when there is no external magnetic field, giving rise to a magnetic domain oriented in the longitudinal direction. When the structure of the magnetic material is thinned down to sub-micron dimensions, it becomes a magnetic nanowire. In an ordinary magnetic nanowire, the individual domains are aligned along the longitudinal direction of the wire, and in this state, a magnetic nanowire is said to have longitudinal in-plane magnetization. This longitudinal in-plane magnetization causes repulsion at the domain boundaries where two N poles or two S poles face in opposite directions, and this repulsion reduces the stability of the magnetic domains. In particular, when a magnetic nanowire is used as a high-density recording medium, the distance between the N and S poles in a domain becomes very short, so the effects from neighboring domains increase and cause further loss of stability. On the other hand, in a perpendicularly magnetized magnetic nanowire produced using materials where N and S poles occur in the thickness direction of the magnetic nanowire, the magnetic fluxes that leak from one domain can enter directly into the neighboring domains that are magnetized in the opposite direction to form closed loops as shown in Fig. 4. These magnetic fluxes preserve the domains very stably. This is analogous to how bar magnets can be stored very stably by keeping them stuck together in pairs with opposite poles stuck together. Increasing the recording density causes adjacent domains with different magnetic poles to come even closer together, so the magnetic fluxes form smaller closed loops that are more rigid and provide even greater stability. However, materials that exhibit perpendicular magnetization are limited to some multilayered films consisted of artificial lattices such as cobalt/platinum, cobalt/palladium and cobalt/nickel, cobalt alloys such as cobalt/chromium and terbium/iron/cobalt, and some ferrites (iron oxides).

2.3 Techniques for creating and driving domains

To use a magnetic nanowire as a recording device, we need some way of creating domains in the magnetic nanowire and moving those domains around. The simplest method for creating domains is the localized application of a strong magnetic field in the

Figure 4: A perpendicularly magnetized magnetic nanowire and its internal magnetization state

Figure 5: Method of generating domains in a magnetic nanowire (Data recording procedure)
same way as the magnetic head on a hard disk drive, as shown in Fig. 5. In parts where a magnetic field is applied, N and S poles occur having the same orientation as the applied field and forming domains in the nanowire.

On the other hand, the domains in a magnetic nanowire can be moved by running an electric current through the wire. The migration of domain walls in the presence of an electric current was first theoretically predicted by Luc Berger about 30 years ago. At that time, nanofabrication of magnetic materials was still in its infancy, and it was impossible to verify this prediction. But with recent progress in fabrication methods such as e-beam lithography, it has become possible to produce magnetic nanowires relatively easily, and Berger's prediction has been proved correct. Figure 6 illustrates the concept of current-driven domain wall motion. As this figure shows, when a current flows longitudinally along a magnetic nanowire, the domain walls inside it migrate in the direction along which the electrons are injected. In this method, since multiple domain walls inside the nanowire migrate simultaneously equal distances, the domains appear to move while remaining intact. However, this phenomenon only occurs when the density of the current flowing through the magnetic nanowire exceeds a certain threshold. This threshold current density depends on the material and structure of the magnetic nanowire. The domain wall migration phenomenon is described in more detail below with reference to Fig. 7. When a magnetic nanowire has domains that are oriented up ($\uparrow$) and down ($\downarrow$), the upward or downward oriented magnetic moments are connected continuously inside the magnetic domains. At the domain walls, the magnetic moment rotates as it changes from up to down (or vice versa). If electrons

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6.png}
\caption{Migration of domain walls and domains in a magnetic nanowire by an applied electrical current}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure7.png}
\caption{Mechanism of domain wall motion in a magnetic nanowire by an electric current}
\end{figure}

\textsuperscript{4} A method for processing and fabricating minute patterns using a very narrow beam of electrons with a spot diameter of a few tens of nm.
are injected from the left side of this magnetic nanowire, the spin directions of electrons, which start out randomly scattered inside the conductor, become aligned in the direction of the magnetic moment (upwards in Fig. 7). Electrons that are uniformly aligned in this spin direction travel to the right inside the magnetic domain, and when they reach the domain wall, their spin directions are gradually bent along the rotation direction of the local magnetic moment inside the domain wall. The reaction to the force that changes the angular momentum of the electrons acts so as to rotate the magnetic moments of the domain wall parts in the opposite direction to the orientation at that point (spin–torque transfer effect). Accordingly, when enough electrons have been injected, the force acting on the magnetic moment of the domain wall parts increases, and as shown at the bottom of Fig. 7, the domain wall migrates to the right. A similar phenomenon occurs at domain walls where the magnetic moment changes from down to up. In other words, it can be said that domain wall migration is a phenomenon whereby the angular momentum of injected electrons is transferred to the magnetic moment.

In theory, domain wall motion should stop as soon as the current is cut off, but in practice, the wall migrates while vibrating during a brief interval afterwards because of the ambient temperature (thermal energy) and the reactance and/or conductance components of the attached wires. Moreover, when an excessive current flows in a magnetic nanowire, the kinetic energy of the injected electrons is transformed into Joule heat by the wire’s electrical resistance, and in the worst case, parts of the wire melt. Furthermore, a DC current applied to a magnetic nanowire generates Joule heat that increases the wire’s resistance, generating even more heat. This leads to a vicious circle, sand it calls for the use of pulse currents with a cool-down interval as a remedy. As such, it is necessary to discover the optimal current and pulse current application conditions in order to induce efficient domain migration with a small current, and various studies have been undertaken with this goal in mind.

### 3. Trends in research into domain driving

Research is being undertaken to clarify and find applications of the phenomenon whereby electrical current causes domain migration. In particular, research aimed at recording devices can be broadly divided into four areas: (a) reducing the current density needed to initiate domain migration, (b) reducing the current while domain migration is taking place, (c) increasing the domain migration speed, and (d) stopping migration stably.

With regard to research area (a), it has become clear that the current density needed to initiate domain migration from a state of complete rest can be reduced by making the nanowire narrower and thinner and by reducing the width of the domain walls. To this end, research is being conducted into the production of very slender nanowires using state-of-the-art e-beam lithography techniques and into clarifying the behavior of domains under an applied current. Regarding (b), it has been shown that domain migration can continue with a smaller current than the current needed to initiate migration. However, to reduce the total energy needed for migration, this current should be reduced further.

Studies relating to (c) have tried to increase the domain migration speed in magnetic nanowires by using various different materials. The domain migration speeds reported so far have been in the range 100–300 m/s, and 300 m/s is about ten times the relative velocity of the magnetic head and disk in an ordinary hard disk drive (about 30 m/s). Faster materials are currently being developed. The studies of (b) and (c) are closely related, and it has been reported that the relationship between a domain’s migration speed $v$ and the current density $i$ needed for migration to continue follows Equation (1):

$$v = \frac{\mu_B pi}{eM_s}$$

Here, $\mu_B$ is the magnetic moment of the electron, $p$ is the spin polarization factor (which expresses the deviation of the electron’s spin direction), $e$ is the electron charge, and $M_s$ is the saturation magnetization in the magnetic material. Equation (1) shows that the domain migration speed $v$ is proportional to the current and inversely proportional to the saturation magnetization. An effective way of making $M_s$ smaller is to reduce the number of magnetic atoms in the magnetic nanowire, but if there are too few magnetic atoms, it becomes impossible to record stably. Research has therefore concentrated on finding the optimal ratio of magnetic atoms by such means as adjusting the number of layers of ferromagnetic and paramagnetic materials at the atomic level. The most commonly used material in magnetic nanowires is cobalt/nickel multilayered film, but since cobalt and nickel are both ferromagnetic, the saturation magnetization is large and this makes it harder to achieve the objectives of (b) and (c) at the same time. At STRL, we are trying instead to make magnetic nanowires from cobalt (ferromagnetic)/palladium (paramagnetic) multilayered films, which exhibit stable perpendicular magnetization. Also, to reduce $M_s$, the ferromagnetic cobalt layers in the films are just two or

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9) $p=1$ when the electron spins are all up, and $p=0$ when equal numbers of electrons have up and down spin. Since the nanowire is always filled from up-spin electrons, the number of down-spin electrons can never exceed the number of up-spin electrons.

10) Materials that are attracted to magnets. They have the property that the magnetization strength rapidly increases in a nonlinear fashion when a magnetic field is applied. The elements that exhibit ferromagnetism at room temperature are iron, cobalt, and nickel.

11) Materials that are not magnetized when there is no external magnetic field, but when an external field is applied, they become very weakly magnetized in the direction of this field. The majority of non-ferromagnetic metals except gold, silver and copper are paramagnetism.
three atoms thick13). As regards (d), research is progressing on magnetic nanowires with features such as constrictions that can act as trap sites for magnetic domains. Magnetic domains must remain immobile when no current applied to the wire, but there are thermally unstable positions at which the domain walls vibrate and move slightly at room temperature. An effective way of putting a stop to this movement is to add domain trap sites to the wire. The efficacy of constrictions and the like at stopping domains can vary. When the effect is weak, it is not possible to completely stop the domains, and conversely when the effect is too strong, a large current density is needed to initiate domain migration. The study of optimal constriction shapes and fabrication methods is currently a hot research topic13[14].

4. Trend of R&D on magnetic nanowire recording devices

Recording devices incorporating magnetic nanowires have been proposed in various forms. Here, we discuss the research trends of magnetoresistive random access memory and racetrack memory, which are typical recording devices based on domain wall motion. We also present a summary of research into sequential memory for video recording, which we are working on at STRL.

4.1 Magnetoresistive random access memory utilizing domain wall motion

Magnetoresistive random access memory (MRAM) consists of an array of memory cells made of magnetic material. It has random access capabilities like those of semiconductor memory, high-speed access, non-volatility, and the ability to be read and written an unlimited number of times. Methods for writing information into an MRAM memory cell include using (a) a current-induced magnetic field, (b) magnetization reversal using spin-torque transfer, and (c) domain wall motion. Here, we will describe the latter of these methods. Figure 8 shows the operating principle of a single-bit MRAM memory cell using domain wall motion15). Data is written in this MRAM by applying an external current that causes the domain wall inside the nanowire to migrate. Reading is performed by a magnetic sensor mounted directly above the nanowire; it detects whether the wire is magnetized up or down. In a practical MRAM device, large numbers of control transistors and array electrodes are formed on a silicon substrate, and the magnetic nanowires and magnetic field sensors are formed thereon. When the control transistors are formed, there is no mixing of impurities such as magnetic materials, so it is possible to reliably produce memory that operates stably.

Domain-wall-motion MRAM is characterized as having a small needed for current for writing data and high data retention and durability. Also, since different current paths are used for writing and reading data, it is easy to make it faster than MRAMs that use current-induced magnetic fields or magnetization reversal using spin-torque transfer.

4.2 Racetrack memory

The racetrack memory is a very innovative type of memory that has a U-shaped three-dimensional

![Figure 8: Operating principle of a memory element using domain wall migration](image)

![Figure 9: Racetrack memory structure](image)
magnetic nanowire structure extending perpendicularly from a substrate. Its structure is shown in Fig. 9. In this memory, the write head creates magnetic domains in the nanowire, and it records data by applying a pulse current to move the positions of these domains. During playback, pulse currents are applied to make the domains migrate until the data (domain) to be read is directly below the read head. Pulse currents can be applied either from left to right or from right to left, so the device has a random access capability, although there is a slight delay when the information to be read is located at the ends of the nanowire. So far, the principles of this device have been validated with a prototype consisting of a magnetic nanowire made of nickel–iron alloy formed on a planar surface, and it has been confirmed to be capable of recording and playing back three to seven bits of data. Although there are still many issues to resolve with racetrack memory, including how best to fabricate U-shaped three-dimensional structures, the advent of longer magnetic nanowires will enable this technology to achieve significantly higher recording densities.

4.3 Sequential memory for video recording

At STRL, we are researching and developing sequential memory for video recording using magnetic nanowires with a view to applying this technology to compact cameras with high resolution and a high frame rate. As shown in Fig. 10, this memory consists of multiple magnetic nanowires arranged in parallel with a pulse current source and a recording head and a playback head at the two ends of each magnetic nanowire. When sequential video data is input at high speed, the data is appropriately segmented and sent to each recording head. Each recording head records the data by forming a series of magnetic domains in the magnetic nanowire. During this process, a pulse current is applied to the magnetic nanowire to shift the domain to the right every time a magnetic domain is formed (corresponding to one data bit). During playback, the domains are moved one bit at a time as the information is read out by the playback heads.

Since this memory contains no mechanical moving parts, it can be expected to be compact, lightweight, and highly reliable. Also, since this is a sequential memory where domains only move in one direction along the magnetic nanowires, it is features a fast operating speed and a simple control system. Furthermore, the linear recording density per magnetic nanowire (i.e., the recording density in the length direction) is considered to be at the same level as that of current hard disks.

So far, we have produced a prototype device with a parallel arrangement of multiple perpendicularly magnetized magnetic nanowires (150 nm wide, made of cobalt/palladium multilayered film) as shown in Fig. 11. We confirmed that once the domains have been fixed, their shape remains unchanged and stable as long as no current flows. Furthermore, as a result of using a 250-nm-wide magnetic nanowire to investigate the changes in magnetic domains when a DC current is applied, we confirmed that the application of a DC current for 10 seconds with a current density of $2 \times 10^7$ A/cm$^2$ caused multiple domains in the magnetic nanowire to migrate by 250 nm without losing their pattern, as shown in Fig. 12. However, in rare cases we have found that when the current is applied, some domains exhibit different behavior from that of the other domains. An example is shown in Fig. 13. When the same current was applied to two magnetic nanowires, the domains migrated by 450 nm at domain walls A and B, but at domain wall C the domain migrated off the side of the picture. In other words, a phenomenon was observed whereby the amount of domain migration differs according to the location of the magnetic nanowire. This could be because a domain that started migrating for some reason failed to stop even after the current had been cut off. In sequential memory for video recording, the domains should migrate by the distance $(L_d)$ needed for writing one data bit, so in order to prevent domains from over-running when a current is applied, we decided to provide the magnetic nanowire with trap sites at intervals of $L_d$ to stop the domains. The results of prototype testing showed that we could reliably stop the domains at fixed distances by providing constrictions and the like as trap sites in the magnetic nanowire, thus showing it may be feasible.
to use magnetic nanowires as the recording medium of sequential memory for video recording.

The experiments reported so far have used DC current to make the domains migrate, but in order to improve reliability and reduce the power needed to drive devices, we are currently testing the application of pulse currents to drive the magnetic domains. We are also working on the core technologies of a working prototype that can record and play back information.

5. Conclusion

We described the principles of domain migration in magnetic nanowires with an applied electric current, and we introduced the research and development of recording devices using magnetic nanowires. A recording device made using magnetic nanowires would be more compact and lightweight and be capable of operating at higher speeds and more reliable than current memory devices. At STRL, we have begun developing sequential memory for video recording using magnetic nanowires.
So far, we have just about finished our experiments to verify the basic principles of this technology, and we are now working on developing the core technologies needed for a prototype device that can record and play back information.

We expect that sequential memory using magnetic nanowires will be applicable to Super Hi-Vision cameras, and we hope to accelerate the pace of our research and development with the aim of developing practical products as early as possible.

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References