Magnetization Analysis of Magnetic Nanowire Memory Utilizing Two Recording Metal Wires for Low Current Recording

K. Ogura, M. Takahashi, N. Nakatani, N. Ishii, and Y. Miyamoto
Science & Technology Research Laboratories, NHK (Japan Broadcasting Corporation) 1-10-11 Kinuta, Setagaya-ku, Tokyo 157-8510, Japan

We have developed magnetic nanowire memories with no mechanical moving parts in order to achieve the large-capacity and ultra-high data transfer rates required for spatial imaging three-dimensional television (3D-TV). In a magnetic nanowire, binary information is recorded by means of a magnetic field induced by two recording wires that are orthogonally fabricated above the nanowire. We simulated the magnetic domain formation process and found that it was formed stably in a magnetic nanowire when we utilized two recording wires. In addition, by adding a certain time difference to the current, the magnetic domains were formed with low current density. We analyzed the behavior inside the magnetic nanowire and found that magnetization reversal can be achieved at low current density when torque is applied at the appropriate time during the precession of the magnetic moment.

Key words: magnetic nanowire memory, magnetization reversal, magnetic domains, current-driven domain wall motion

1. Introduction

We have been developing magnetic storage devices that work with huge amounts of data at ultra-high speed to be utilized for future 3D-TV storage. Since the data transfer rate required for storage devices in spatial imaging 3D-TVs \(^{10}\) (light field spatial imaging) is expected to exceed at 1 Tbps, which is far faster than that of uncompressed ultra-high definition TV (144 Gbps), it is extremely difficult to utilize existing memories, such as HDDs or SSDs. There is therefore a need to develop a new one that has both a large capacity and a high transfer rate, and that can hold data for a long time. Many researches on utilizing a magnetic nanowire as a memory have been reported \(^{2-4}\) in recent years and they are also promising candidates for future 3D-TV storage devices. Unlike HDDs, which have a magnetic head and a disk drive mechanism, magnetic nanowire memories contain no mechanically moving parts and domain walls are driven at high speed by spin transfer torque \(^{5}\). Also, by synchronizing the parallel operation of many nanowires, they have the advantage of further high data transfer rate \(^{6-8}\).

We have already succeeded in driving multiple magnetic domains along magnetic nanowire \(^9,12\) and forming magnetic domains in nanowire by magnetic recording head used in HDD \(^{13}\). However, in order to use it as a real device, it is necessary to form magnetic domains at a lower recording current and all the components, i.e. magnetic nanowire media, insulator, writer and readers, should be integrated onto silicon wafer substrates. For the racetrack memory, writing data is accomplished by a current magnetic field induced by a single metal wire \(^14\). We consequently developed a recording method utilizing two metal wires for stable and low current domain formation \(^{15}\). In this study, we propose a method for adding a time difference to the current applied to the two metal wires and managed to record binary information at a lower current. The purpose of this work is to analyze the behavior of the magnetic moment and to determine the mechanism underlying the lower current recording.

2. Magnetic nanowire memory

As shown in Fig. 1, the memory consists of a large number of magnetic nanowires, which are fabricated to be a couple of hundred nanometers wide and two recording metal wires. The recording wires are orthogonally arranged above the magnetic nanowires. The flow of the memory operation is as follows: First, we apply a magnetic field induced from each recording wire to the magnetic nanowires by sending a pulse current to each recording wire in the opposite direction. Magnetic domains are then formed directly below the gap between the two recording wires using the synthesized magnetic field to record information. Next, a driving pulse current is applied to the left side of the magnetic nanowire to shift the magnetic domains at high speed. By repeating these recording and driving operation, the magnetic nanowire accumulates the magnetic domains. Finally, these stored magnetic domains are detected and reproduced with a tunnel magnetoresistance (TMR) head.

![Fig. 1 Magnetic nanowire memory.](image-url)
3. Micromagnetic simulation

3.1 Simulation model

We analyzed the behavior of the magnetic moment during the magnetic domain formation process by micromagnetic simulation using the Landau-Lifshitz-Gilbert (LLG) equation. The nanowire model used in the calculation is shown in Fig. 2. The magnetic nanowire is rectangular and measures 1.6 μm long, 120 nm wide (Wn), and 12 nm thick (Hn). The recording wire is 2 μm in length (Ln) and has a 120 nm square on each side in cross section (Wn, Hn). The gap between the two recording wires is 100 nm (Sn), and an air gap between the recording wires and the magnetic nanowires as an insulating layer is 10 nm. The magnetic nanowire was divided into 4 nm cube meshes for calculation from the perspective of calculation accuracy.

3.2 Simulation conditions

The recording currents Ia and Ib (current density: j) shown in Fig. 3 were respectively applied to recording wires A and B in the opposite direction with a time difference T. We calculated the magnetic domain formation below the gap after 2 ns of applying the current. The parameters of the recording current and the magnetic properties of the magnetic nanowire are listed in Table 1. The initial magnetization direction was set to the +z direction.

![Fig. 2 Simulation model of magnetic nanowire memory.](image)

**Table 1** Magnetic properties and recording current parameters of magnetic nanowire.

| Magnetic nanowire | Recording current |
|-------------------|-------------------|
| Anisotropic magnetic field: | 5 |
| Hk (kOe) | Pulse width: |
| 3.14 | (ns) |
| Ic: 2 | 1.2×10^-11 |
| Ic: 2-T | Current density: |
| 3.3×10^8 |
| Exchange coupling constant: | 0.15 |
| A (J/m) |
| Saturation magnetization: | 4πMs (T) |
| 5 |

Fig. 3 Pulse diagrams of recording current applied to two metal recording wires. The current density of Ia and Ib is set so that magnetization reversal cannot occur when Ia and Ib are applied simultaneously without time difference.

3.3 Simulation results

Fig. 4 shows the analysis results of the magnetization after 2 ns of the current applied to two recording wires. For (a) a single recording wire, the left end of the magnetic wall was stable and formed a straight line. However, the right edge of the domain wall was swaying throughout the calculation and was not stable at the end, indicating that more time was required for the magnetic domain to stabilize. In this case, the recording currents of 110 mA which is the minimum value to successfully form the magnetic domain was applied. In contrast, for (b), when recording currents Ia and Ib were applied to the recording wires in the opposite direction with no time difference, the minimum recording current was around 60 mA which is lower than the current needed for a single recording wire. Moreover, when recording currents were applied with a time difference of T = 0.15 ns the minimum recording current was around 50 mA, which means we succeeded in reducing the recording current by 10 mA. This was because the magnetic field induced by the current was generated symmetrically from each recording wire, and the z component of the synthetic magnetic field was uniformly distributed around the gap between the two recording wires.

Next, to examine the tolerance, we calculated the magnetic domain formation in the case when the pulse currents Ia and Ib, shown in Fig. 3, were applied to the recording wires A and B in the opposite directions with a time difference of T = 0–0.25 ns (0.01 ns step). We found that the magnetic domain was specifically formed around T = 0.05 ns and T = 0.15 ns. Fig. 5 shows the magnetic domain formation after 2 ns of the current applied to the recording wires. These results demonstrate that it is possible to reverse the magnetization in the magnetic nanowires just below the recording gap in the range of time differences T = 0.03–0.08 ns and T = 0.15–0.18 ns, and that there was a difference in each magnetic domain formation process.

In this paper, we focus on the typical behavior of the magnetic moment at T = 0.15 ns, as the clearest simulation results of magnetization reversals including nucleation and domain wall propagation were obtained for this timing.

![Fig. 4 Spatial distributions of magnetizations at elapsed time of 2 ns.](image)
4. Analysis of magnetization reversals

Fig. 6 shows the spatial distribution of the magnetizations after 0.1 ns in the process of magnetic domain formation when the time difference of \( T = 0.15 \) ns was provided. We can see that the magnetization reversal at the \( \alpha \) point (50 nm, -58 nm, 6 nm), which is the core of the magnetic domain formation, was induced at first, and then a reversed magnetic domain was spread and formed in the entire gap between the recording wires by diffusion propagation of the magnetic wall 16). We therefore focused our analysis on the temporal changes of the magnetic moment at \( \alpha \) point and at \( \beta \) point (2 nm, 2 nm, 6 nm), which is near the origin, as the representative points of the propagation.

The magnetization trajectory at the time of magnetization reversal at \( \alpha \) and \( \beta \) points is shown in Fig. 7. At \( \alpha \) point (red line), precession was induced in the magnetic moment after the current was applied to recording nanowires, and the magnetic moment reversed after passing through a complicated path several times while pointing in the +z direction. Since \( \alpha \) point was the core of the magnetization reversal (as described above), whether or not magnetic domains were formed in the gap depended on the feasibility of the magnetization reversal at \( \alpha \) point. On the other hand, at \( \beta \) point (blue line), the magnetic wall propagated due to the interaction of the magnetic moments between the neighboring meshes and the magnetic reversals occurred in a short time.

Fig. 8 shows the time variation of the \( z \) component of the magnetic moment after the recording current \( I_0 \) was applied. Here, the magnetization trajectory that occurred when recording current \( I_0 \) was applied at \( t = 0 \) and \( I_0 \) was applied with a time difference of \( T = 0.14 \)–0.19 ns is also shown. For the time differences of \( T = 0.14 \) ns and \( T = 0.19 \) ns (dotted lines), the magnetic moment failed to reverse even after the torque was applied by the recording current \( I_0 \). In contrast, in the range of \( T = 0.15 \)–0.18 ns (solid line), the magnetic moment succeeded in reversing, which indicates that the magnetization reversed while oscillating in the \( z \) direction. When we examined the first time at which the \( z \) component of the magnetic moment turned negative, i.e., below zero, we found that magnetization reversal in the case of \( T = 0.16 \) ns and \( 0.17 \) ns commenced in a relatively short time (\( t = 0.25 \) ns).

In the range of \( T = 0.15 \)–0.18 ns, where magnetization reversal occurred, there was a slight difference in the process of reversal depending on the time difference \( T \). This indicates that the feasibility of the magnetization reversal is related to the position at which the recording current \( I_0 \) applied the torque to the precession of the magnetic moment at \( \alpha \) point. Therefore, we next investigated the relationship between the magnetization trajectory and the time when the torque superposition commenced.

The magnetization trajectory at \( \alpha \) point, the core of the magnetic domain formation, is shown on the \( x'y \) plane in Fig. 9. First, the magnetic moment started its precession from the origin, and after drawing a larger circle counterclockwise for 0.11 \( n \) s, it entered the second track. Here, we overlay the magnetization trajectory when the recording current \( I_0 \) was applied with the time difference \( T = 0.14 \)–0.19 ns. We found that when a torque was applied to the precession of the magnetic moment, the subsequent magnetization trajectory changed in accordance with the time difference \( T \). At the time difference \( T \) indicated by the red dotted line, magnetization reversed in a relatively wider range on the left side of the larger magnetization trajectory (second and third quadrants) and in a narrow range on the left side of the second track of the precession.
Our future work will involve investigating the physical significance of the optimal torque position (in the range of 150°–225°) for the precession. We analyzed the behavior of the magnetization to determine the appropriate range of the time difference and found that there was a close relationship between the precession and the position where the torque was applied by the current $I_0$, and that the magnetization reversed in a specific range on the magnetization trajectory.

Overall, we demonstrated that our method of forming magnetic domains by controlling the time difference between the currents applied to the two recording wires is very useful. In a real device, it is possible to adjust the time difference between the two recording currents with an ultrashort pulse generator, or to determine the extra length of the U-shaped recording wire to create the appropriate time difference.

In future work, we will conduct a more detailed analysis and verify the range of the time difference in the case of multiple interacting magnetic nanowires.

4. Conclusion

We have proposed a magnetic nanowire memory with two recording wires and analyzed the magnetic domain formation process by micromagnetic simulation. Results showed that magnetic domains were successfully formed by low current density in a magnetic nanowire when a current in the opposite direction with an appropriate time difference was applied to the recording wires. We analyzed the behavior of the magnetization to determine the appropriate range of the time difference and found that there was a close relationship between the precession and the position where the torque was applied by the current $I_0$, and that the magnetization reversed in a specific range on the magnetization trajectory.

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