Magnetic logic devices composed of permalloy dots

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Abstract. Magnetic logic devices have been investigated by micromagnetics simulation and experiment. The simulation shows that the magnetic logic devices composed of 4 elliptical permalloy dots perform both the NAND and NOR logic operations. The experiments indicate that the distance between adjacent dots must be shorter than 50 nm and 70 nm along the long axis and the short axis of the dots, respectively. The micro-fabricated test devices show the above logic operations.

1. Introduction

Spin-electronics devices such as magnetic random access memories[1-2], microwave oscillators[3] and spin torque diode[4] have been investigated as future magnetic functional devices. The magnetic logic devices[5] have also been investigated. However, the reported logic devices used many magnetic dots, and thus they could not be small. Recently, we have proposed new structures for magnetic logic devices, based on the theoretical investigation using the Landau-Lifshitz-Gilbert equation[6]. The magnetic logic devices consist of 4 elliptical permalloy (Ni-20at%Fe) dots. The size of each dot is 80 nm x 40 nm, and the distance between adjacent dots is 20 nm. Because of the narrow distance, the neighboring magnetic dots are magnetically coupled due to magnetostatic interactions, and the coupling produces both the NAND and NOR logic operations. Moreover, the small sizes and narrow distances allow the high-density arrangement, so that the size of the logic devices can be small. However, there is a difficulty to micro-fabricate the narrow distances between adjacent dots.

In this study, we experimentally investigate the effect of the distance between adjacent dots on the magnetostatic interactions between the dots. If larger distance allows the magnetostatic interactions, the logic devices can be easily micro-fabricated.

2. Experimental procedures

The Ni-20at%Fe (permalloy) dot arrays were micro-fabricated by electron beam lithography, electron beam evaporator and lift-off method on Si(100) substrates with thermally oxidized layers. The magnetic fields of 40 kA/m were applied to the substrates in order to introduce uni-axial anisotropy along the long axis of the elliptical dots. The thickness of the dots was 10 nm. The aspect ratio of the elliptical dots was 1:2. The long axis was changed between 200 and 1600 nm. The distance between the adjacent dots was also changed.
The magnetization processes of the dot arrays were observed using a longitudinal magneto-optical Kerr effect (MOKE) magnetometry at room temperature. The magnetic field was applied along the long axis of the dots, and was between -1 and 1 kOe. The shape of the dot arrays was observed by scanning electron microscopy (SEM) and magnetic force microscopy (MFM) observed the magnetic states of the dot arrays. Magnetic configuration computations were conducted using the Landau-Lifshitz-Gilbert (LLG) equation and the finite element method[7]. The following parameters for Ni-20at%Fe were assumed: saturation magnetization $M_s=1$ T, exchange constant $A=1.05\times10^{-11}$ J/m, uniaxial anisotropy constant $K_u=100$ J/m$^3$.

### 3. Results and discussion

**3.1. Optimum structure obtained using micromagnetics simulation**

The optimum structure of magnetic logic device obtained using micromagnetics simulation is shown in Fig.1[6]. The magnetic logic device consists of 4 elliptical permalloy dots. The size of each dot is 80 nm x 40 nm, and the distance between adjacent dots is 20 nm. The three dots “Input A-C” are used to input data. Each dot for input data magnetically couples with the dot (output Z) to output data. The total of three magnetostatic interactions produce the logic operations.

The simulated magnetic configurations of logic device are shown in Fig. 2. The green color means the leftward magnetization, and it means information of zero. On the other hand, the red color means the rightward magnetization, and it means information of one. There are 8 input patterns as shown in Fig. 2.

![Figure 1. An optimum structure of magnetic logic device obtained using micromagnetics simulation.](image1)

![Figure 2. Simulated magnetic configurations of logic device. The green and red mean the leftward and rightward magnetization, and also mean information of zero and one, respectively.](image2)
The simulated results are summarized in Table 1. As shown in Table 1, when the input A is “zero”, there are 4 patterns for the inputs B and C. The inputs B and C change the output Z. The output Z becomes the result of “NOR” operation for the inputs B and C. On the other hand, when the input A is “one”, there are also 4 patterns for the inputs B and C. The output Z becomes the result of “NAND” operation for the inputs B and C. As a result, the input A decides the kind of logic operation, “NOR” or “NAND”. It can be good advantage for the magnetic logic devices.

3.2. Magnetostatic interactions between magnetic dots
As mentioned above, the micromagnetics simulation indicates the operation of the magnetic logic device composed of 4 elliptical permalloy dots. The optimized distance between adjacent dots is 20 nm. The distance cannot be easily micro-fabricated. Therefore, we experimentally investigated the limit of the distance between adjacent dots that cause the magnetostatic interactions.

As shown in Fig. 1, there are two sequences in the magnetic logic devices. They are longitudinal and transverse. Figure 3 shows the schematic illustration and magnetization curves for the longitudinal sequence. In the sequence, the magnetostatic interaction between adjacent dots is parallel, and thus the stray field is applied along the anti-parallel direction to the applied magnetic field before the switching of the magnetization, as shown in Fig. 3(a). If the stray field $H_{st}$ is zero, the magnetization of dots switches at the intrinsic switching field $H_{sw,int}$. On the other hand, when the stray field $H_{st}$ is not zero, the stray field decreases the total field applied to the magnetic dots. The decrease of total field increases the switching field $H_{sw}$ which is applied magnetic field to switch the magnetization of the dots. Therefore, the switching field $H_{sw}$ becomes high as shown in Fig. 3.

**Table 1.** Simulated results of logic device.

| A | B | C | Z | NOR | NAND |
|---|---|---|---|-----|------|
| 0 | 0 | 0 | 1 | NOR |      |
| 0 | 0 | 1 | 0 |      | NAND |
| 0 | 1 | 0 | 0 |      | NAND |
| 0 | 1 | 1 | 0 |      |      |
| 1 | 0 | 0 | 1 |      |      |
| 1 | 0 | 1 | 1 |      |      |
| 1 | 1 | 0 | 1 |      |      |
| 1 | 1 | 1 | 0 |      |      |

**Figure 3.** (a) schematic illustration and (b) magnetization curves for the longitudinal sequence.

Figure 4 shows changes in the switching field due to the distance between adjacent dots $D_a$ [8]. The long axis $a$ of the dots is changed from 200 nm to 1600 nm. The field is applied along the long axis of the dots. As shown in Fig. 4, the switching field increases at 50 nm as the distance decreases. Therefore, it is understood that the magnetostatic interactions is produced when the distance is 50 nm and less than 50 nm. It is longer than the optimized distance by simulation.

Figure 5 shows the schematic illustrations and magnetization curves for the transverse sequence. In the sequence, the magnetostatic interaction between adjacent dots is antiparallel. As shown in Fig. 5 (a), the stray field caused by upper dot is applied to the lower dot, and the direction is parallel to the applied magnetic field before the first switching. Therefore, the stray field helps the first switching, and thus the first switching field decreases as shown in (c). The magnetizations of the half of dots switch at the first switching field, and thus the magnetic configuration of the dots becomes antiparallel after the first switching. After the first switching, as shown in Fig. 5 (b), the stray field caused by the switched lower dots is applied to the upper dot. The direction of stray field is anti-
parallel to the applied magnetic field between the first switching and the second switching. Therefore, the stray field disturbs the second switching, and thus the second switching field increases as shown in (c).

Figure 4. Changes in the switching field due to distance between adjacent dots.

Figure 5. (a), (b) schematic illustrations and (c) magnetization curves for the transverse sequence.

Figure 6 shows changes in the second switching field due to distance between adjacent dots $D_b$. The long axis $a$ of the dots is changed from 200 nm to 1600 nm. The field is applied along the long axis of the dots. As shown in Fig. 6, the switching field increases at 70 nm as the distance decreases. Therefore, it is understood that the magnetostatic interaction is produced when the distance is 70 nm and less than 70 nm. It is longer than the optimized distance by simulation.

Figure 7 shows the MFM images and schematic illustrations of micro-fabricated test devices. We have made a lot of test devices that structures are shown in (e), and observed their MFM images as shown in (a)-(d). When we select the MFM images that input A is “one”, all images have the pattern shown in (a)-(d), which indicate the “NAND” operations. On the other hand, when we select the MFM images that input A is “zero”, all images indicate the “NOR” operations (not shown here).
4. Summary
We have investigated the magnetic logic devices. The micromagnetics simulation shows that the magnetic logic devices composed of 4 elliptical permalloy dots perform both the NAND and NOR logic operations. However, the optimized distances between adjacent dots are 20 nm in the results of simulation. The distances of 20 nm are very difficult to be micro-fabricated. On the other hand, the experimental results show that the distance between adjacent dots must be shorter than 50 nm and 70 nm along the long axis and the short axis of the dots, respectively. The experimental results indicate that it is not so difficult to micro-fabricate the magnetic logic devices.

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