Clock field in arrayed magnetic logic gates with a magnetic force microscope tip

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Abstract. A magnetic logic gate (MLG), which is based on magnetic quantum dot cellular automata (MQCA), is capable of NAND/NOR logic operations. By arranging MLGs in a two-dimensional periodic array, a highly functional circuit can be created. However, NAND/NOR gates are difficult to form into a two-dimensional periodic arrangement. Here, we propose NOT/AND/ORs gate based on MLGs, which can be arranged in a two-dimensional periodic array. To demonstrate logic operations, we performed numerical simulations based on the macro-spin model. To execute logic operation in the arrayed structure, we used the stray field from a magnetic force microscope tip.

1. Introduction
A magnetic logic gate (MLG)[1], which is based on magnetic quantum dot cellular automata (MQCA) [2], can perform NAND/NOR logic operations via magnetostatic interactions between adjacent magnetic dots. The MLG has the advantages of high integration density, information non-volatility, high resistance to ionized radiation, low dissipation energy and stability at room temperature. In general, the MLG is composed of elliptical dots. The dots are small enough to take a single-domain state. Because of their shape anisotropy, the magnetization directions of the dots at remnant states are bistable. Therefore, digital information of “0”“1” can be stored as the direction of dot magnetization. Logic operations are executed by applying an external magnetic field (clock-field). In previous studies, a NAND/NOR gate [3] and a similar gate [4] were experimentally demonstrated.

By arranging the gates in a two-dimensional periodic array, we can create highly functional circuits. However, NAND/NOR gates are difficult to form into a two-dimensional periodic arrangement. In the NAND/NOR gate, input dots are placed on the easy/hard axis of the output dot. Therefore, the number of adjacent dots, which defines the behavior of the gate, changes when the gates are arranged in a two-dimensional periodic array.

In this study, we propose NOT/AND/OR gates that can be arranged in a two-dimensional periodic array. To demonstrate local logic operations of the NOT/AND/OR gate, we performed numerical simulations using a macro spin model. To apply a local clock field to the gate, we use the stray field from a magnetic force microscope (MFM) tip.
2. NOT/AND/OR gate

Figures 1(a) and (b) show schematic diagrams of the NOT/AND/OR gate. The gate is composed of three input dots ($I_A$, $I_B$, and $I_C$) and an output dot ($O_Z$). The binary states of 0 and 1 correspond to negative and positive polarity of the $x$ component of the dot magnetization, respectively. $I_A$ and $O_Z$ are anti-ferromagnetically coupled, whereas $I_B$ and $O_Z$ or $I_C$ and $O_Z$ are ferromagnetically coupled. The magnetization vector of the $O_Z$ points parallel to the direction of the majority stray field from $I_A$, $I_B$ and $I_C$. Therefore, the gate works as a NOT/AND/OR gate \[ (I_C = I_B; O_Z = \overline{I_A}), (I_A = 0; O_Z = I_B \lor I_C), (I_A = 1; O_Z = I_B \land I_C) \]. By sharing the dots with adjacent gates, the NOT/AND/OR gates can be arranged in a two-dimensional array [Figure 1(c)].

3. Simulation methods

In our numerical simulation, we made four assumptions. (1) Each dot occupies a single-domain state. This is a good assumption when the dot size becomes smaller than the 100-nm semi-major axis. (2) The MFM tip is assumed to be a magnetic dipole. (3) The magnetization of the dots is in the \( x-y \) plane, based on the demagnetization of the dots by thin films. (4) The major interaction between the dots and the tip is a magnetostatic interaction. For Permalloy dots with a gap wider than 10 nm, other factors such as the exchange interaction between the dots and the intrinsic anisotropy were negligible. Similar approaches were taken in studies of coupled nanomagnets [5]. The total energy of the gate is

\[
E = -\sum_i \mu_0 m_i \cdot \left( H + \frac{1}{2} \sum_{j} N_{i,j} M_j \right),
\]

where \( m_i, M_j, H \) and \( \mu_0 \) are the magnetic moment of dot \( i = I_A, I_B, I_C, O_Z \), the magnetization of dot \( j \), the clock field and the permeability of a vacuum, respectively. \( N_{i,j} \) is the demagnetization tensor. When \( i = j \), \( N_{i,j} \) is calculated from the demagnetizing factor of the ellipsoid [6], and \( N_{i,j} \) for \( i \neq j \) is calculated by averaging the stray field [7] from dot \( j \) at each point in dot \( i \) in 10-nm steps. After \( H \) is changed, we calculate the metastable/stable state of the system by oscillating the magnetization of the dots at an angle of 0.1°. The parameters used here are as follows: \( |m| = 800 \text{ kA/m}, r_x = 50 \text{ nm}, r_y = 30 \text{ nm}, r_z = 30 \text{ nm}, \) \( d_{x,\text{MLG}} = 108 \text{ nm}, d_{z,\text{MLG}} = 44 \text{ nm}, t = 20 \text{ nm} \). The magnetization and volume of the MFM tip are 800 kA/m and \( 1 \times 10^{-21} \text{ m}^3 \), respectively.

4. Results and discussion

Figures 2(a-d) show the threshold tip position for magnetization reversal of $O_Z$. The $y$ positions of the tip are fixed at 0 nm. Based on the symmetrical shape of the gate, binary states of $I_A$ are fixed at 1. The initial binary states of the input dots in Figure 2(a-d) are $(I_A, I_B, I_C) = (1, 1, 1), (1, 0, 1), (1, 1, 0)$ and...
Figure 2. Threshold tip position for magnetization reversal of OZ. Initial binary states of input dots are (a) \((I_A, I_B, I_C) = (1, 1, 1)\), (b) \((1, 0, 1)\), (c) \((1, 1, 0)\) and (d) \((1, 0, 0)\). (1, 0, 0), respectively. The circle and cross symbols represent the tip positions where the magnetization of OZ shows the correct logic operation results \((O_Z = I_B \text{ OR } I_C)\) and erroneous results \((O_Z \neq I_B \text{ OR } I_C)\), respectively. To set the binary state of 0 or 1 to OZ, the MFM tip should be oscillated along the \(x\) axis. When we fix the center of the oscillation at \(x = 0\), the threshold heights corresponding to the correct operation results are higher than those for the erroneous operation results. Therefore, by retracting the tip from the sample surface, we can execute the logic operation using the stray field from the MFM tip.

Figures 3(a) and (b) show MFM tip motion for the logic operation. The threshold heights corresponding to correct logic operation at \(|x| = 4 \text{ nm}\) are 35 nm, 32 nm, 39 nm and 37 nm, respectively. On the other hand, those corresponding to the erroneous operation results are 32 nm, 31 nm, 37 nm and 30 nm, respectively. Therefore, to execute the logical operation, the tip is oscillated along the \(x\)-axis with an amplitude of 4 nm and lifted from 30 nm to 39 nm. Figure 3(c) shows the \(x\) component of the stray field from the MFM tip at the center of OZ. The stray field is oscillated as a chopping wave and the amplitude is decreased from 82.0 kA/m to 57.7 kA/m.
Figures 4(a-d) show the change of the magnetization angles of the dots with MFM tip motion. The initial binary states of the input dots are (I_A, I_B, I_C) = (1, 1, 1), (1, 0, 1), (1, 1, 0) and (1, 0, 0) respectively. When the tip-sample distance is less than the threshold heights, the magnetizations of O_Z are oscillated due to the MFM tip motion. When the tip reaches the threshold height, the binary state of O_Z is fixed to the NOT/AND/OR logic operation results. The threshold heights are 33 nm, 32 nm, 38 nm and 31 nm, respectively. It is noteworthy that disturbances to the magnetization angle of the input dots by the MFM tip are negligible. Therefore, we can locally execute logic operations of arrayed NOT/AND/OR gates with an MFM tip.

5. Summary
We demonstrate NOT/AND/OR gates, which can be arranged in a two-dimensional periodic array, with an MFM tip. The clock field from the MFM tip can be considered as a localized oscillating magnetic field. By using a bit line and a word line of a general MRAM circuit, a similar clock field can be applied to the arrayed MLG structures without mechanical moving parts such as the MFM tip. With arrayed MLG structures, highly functional circuits such as adder circuits will be realized in the near future.

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