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## Magnetic logic gate for binary computing

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### Abstract

We have demonstrated that a suitable arrangement of ferromagnetic elliptical nanodots having dimensions less than 100 nm is able to execute logical NAND and NOR operations. This is named as magnetic logic gate (MLG). The NAND and NOR operations are known as universal gate which are able to execute all fundamental logical operations. For a certain range of the external magnetic field, the magnetization of the elliptical dots takes place only along the major axis because of strong uniaxial shape anisotropy. This inherent binary nature of the dots enables them to be used in the MLG. The MLG possesses number of advantages including high integration density, fast operation and non-volatility.

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**Keywords:** Magnetic logic gate; Spin computing; Ferromagnetic nanodot; Binary ferromagnetic dot; Shape anisotropy; Universal gate; NAND gate; NOR gate; Micromagnetic simulation; Single domain; Permalloy; Three-dimensional hardware; High integration density

### 1. Introduction

In recent years, ‘nanotechnology’ has established itself as a catchword humming through the ranks of the scientific arena. Nanotechnology of magnetism is revealing new and exciting thoughts which afterward emerge as cutting edge technologies [1,2]. This branch of nanotechnology has already proven its high and reliable efficiency in storing binary information as well as in reading and writing the information. Going one step ahead, by achieving digital logic gate operation in this arena, one could dream a total computing system using magnetic logic gate (MLG). Logical operation based on electron spin is a new challenge because silicon transistor based modern computing is facing some limitations as the devices approach nanometer dimensions [3,4]. We have demonstrated that ferromagnetic nanodots are efficiently able to perform logical operations necessary for the binary computing, named as MLG.

In order to search for the alternative technology for digital computing, research in various directions is in progress [5–13]. Many of these approaches do not consider electron spin but electron charges. As soon as the magnetism is concerned, the spin of the electron eventually

plays role along with the charge. Inclusion of the spin adds advantageous features like non-volatility, miniaturization and enhanced speed. The MLG certainly makes use of the spin.

### 2. An inherently binary ferromagnetic nanodot

The design of the MLG requires picking appropriate ferromagnetic nanodots which will be its building blocks. Here, the word ‘appropriate’ categorically means existence of strong uniaxial shape anisotropy and keeping at single domain state. On a small enough length scale, the ferromagnetic dots are likely to have strong shape anisotropy, which eventually introduces some preferential directions of the magnetization vector. In this case, the vector may not always follow the external magnetic field. The preferences could be affected by the dot’s shape, size and thickness along with others. The Permalloy elliptical dots are found to be highly suitable for representing and processing spin based binary information from the above point of views. The suitability of the dots to be used in the MLG is investigated by applying uniform rotational field of 500 Oe on it. The magnetization and domain orientation are observed by micromagnetic simulation using Landau–Lifshitz–Gilbert equation [14]. Fig. 1(a) presents angle

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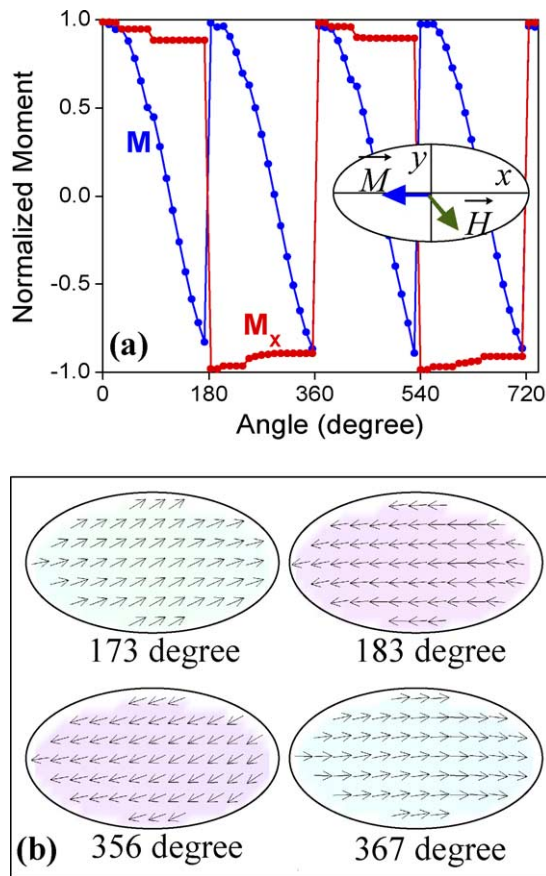


Fig. 1. Binary nature of elliptical Permalloy dot (a) Normalized value of  $M$  and  $M_x$  in rotational field. (b) Existence of single domain state at switching.

versus magnetization plot of an elliptical dot having major axis, minor axis and thickness of 80, 40, and 10 nm, respectively. Here,  $M$  represents scalar product of normalized magnetization vector and a unit vector along the applied field. On the other hand,  $M_x$  represents magnitude of  $x$  component of the normalized magnetization vector. It is evident from the figure that the magnetization vector does not follow the external magnetic field but the vector nearly remains fixed along  $+x$  direction for rotations of the field from 0 to 173°. For further rotation of the magnetic field, the magnetization vector switches very sharply from  $+x$  to  $-x$  direction and again remains fixed over the next half cycle. This process repeats over consecutive rotations of the field. The dots are found to remain at single domain state even at switching as shown in Fig. 1(b). In this figure, the top two demonstrate the first switching from 173 to 183° in Fig. 1(a), and the bottom two are of the second switching from 356 to 367°. This 180° transition of the magnetization vector is found to take place very sharply and there appears no intermediate state between the two states. Thus, the magnetization vector of this elliptical dot has only two preferential directions along its major axis. Additionally, the elliptical dots are perfectly in single domain state. The exclusive feature of such binary nature of the elliptical dot enables it to be used in the magnetic logic gates.

In implementing the MLG, the binary logic states '0' and '1' are defined as the magnetization vector points towards  $-x$  and  $+x$  directions, respectively, along the major axis of the ellipse. This ensures that the MLG uses identical logic definitions for all logical operations.

### 3. The magnetic logic gate and logical operations

Having the appropriate elliptical dots, the MLG is designed as illustrated in Fig. 2. Depending on the desired logical input, the input dots, namely  $A$ ,  $B$  and  $C$  are individually magnetized by 500 Oe of magnetic field. The micromagnetic simulation is carried out for all possible combinations of the binary inputs and the results are presented in Fig. 3. The output dot  $Z$  is found to be magnetized distinctly along either  $+x$  or  $-x$  directions and in all cases the dots are in single domain state. The dots are allowed to magnetize from random initial state. Since the output dot is not exposed to the external magnetic field, its magnetization is determined by the resultant of the classical magnetostatic interaction caused by the input dots. Because of the binary nature of the elliptical dot, the dot  $Z$  magnetizes only in two directions along the major axis and it is also influenced by the majority of the magnetization state of the input dots. However, it is worth mentioning that the effects of the interaction between the dots  $A$  and  $Z$ , and interaction between the dots  $B$  and  $Z$  are not similar in nature. For an isolated system, having the dots  $A$  and  $Z$  only, magnetization direction of the dot  $Z$  will be the same as of  $A$ . Thus, the logical state of the output will be always same to that of the input  $A$ . On the contrary for the dots  $B$  and  $Z$  only, the magnetization in the dot  $Z$  will point always opposite to that of the input  $B$ . Thus, the logical states of  $B$  and  $Z$  will be always opposite to each other. Same thing will happen in case of  $C$  and  $Z$ . The time required to magnetize the input and to settle down the output dots is found to be in between 1.4 and 2.4 ns as noted in Fig. 3. The average time required is 1.8 ns. By summarizing the logical states of the inputs and output of the simulation results of Fig. 3, the truth table presented in Table 1 is readily obtained. This truth

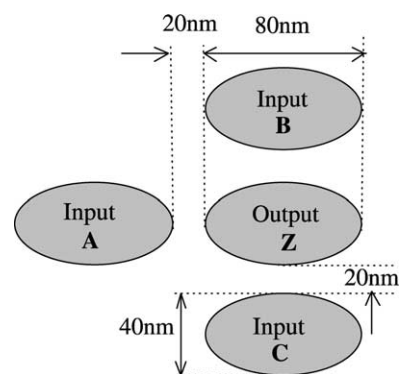


Fig. 2. Magnetic logic gate (MLG) architecture that performs logical NAND and NOR operations. Each elliptical Permalloy dot is 10 nm thick.

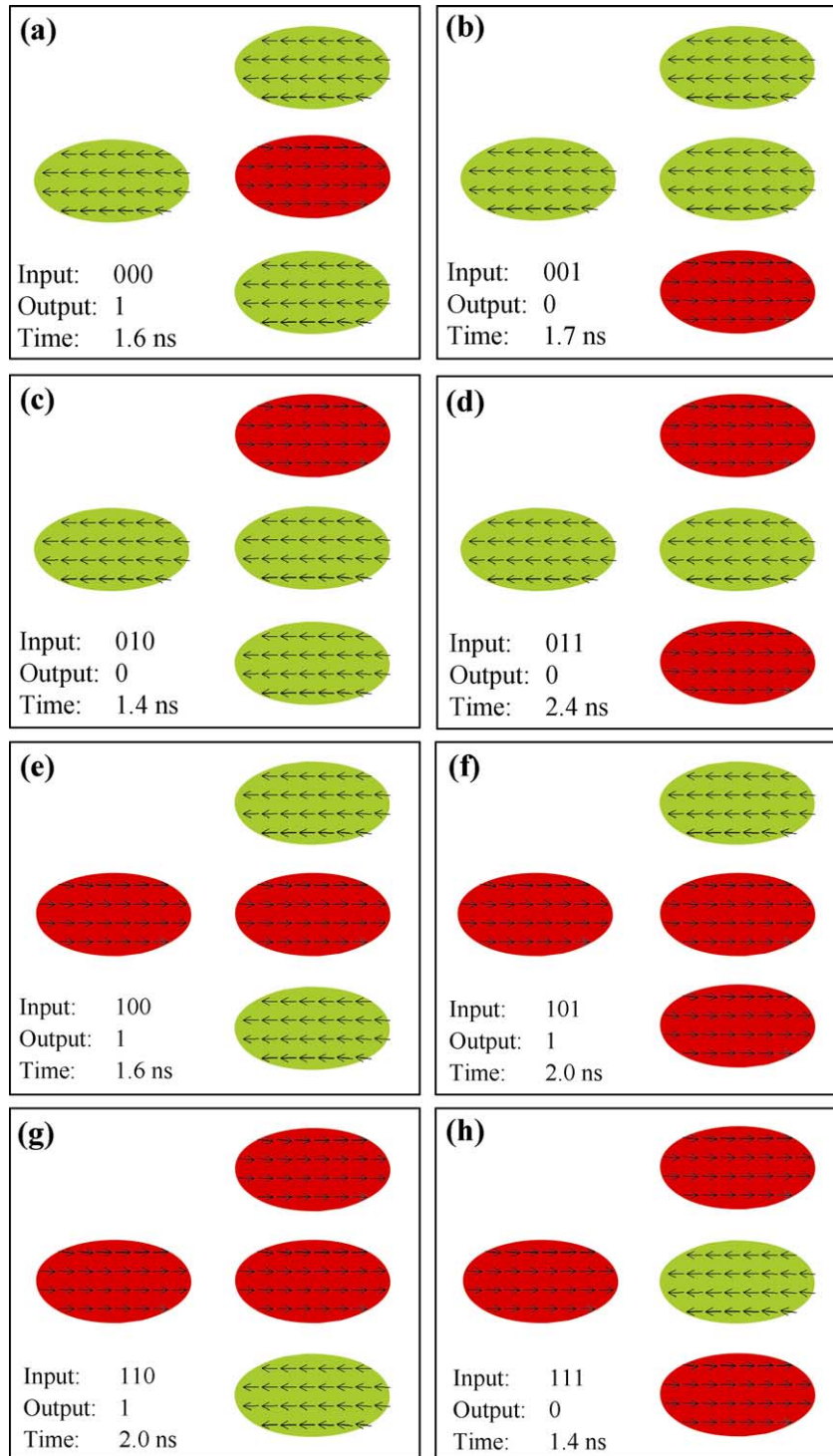


Fig. 3. Domain and magnetization vector of the MLG for all possible logical inputs: (a) 000, (b) 001, (c) 010, (d) 011, (e) 100, (f) 101, (g) 110 and (h) 111. Green and red indicate single domain state pointing the vector left and right, respectively. Logic definitions: '0' = left, '1' = right.

table clearly shows that the MLG performs NAND and NOR operations depending on the logical state of the input A. When the dot A remains at logical '1' state the MLG functions as NAND gate and it functions as NOR gate while the dot's logical state is kept at '0'.

It is well known from the elementary Boolean algebra that the two universal gates, namely NAND and NOR are

independently able to perform all fundamental logic operations, namely AND, OR and NOT. For instances, AND operation using only NAND gate, and OR operation using only NOR gate requires two units of NAND gate and two units of NOR gate, respectively. By cascading the fundamental logical gates in a real digital circuit, one could achieve any desired logical operation although this might



Table 1  
Summary of Fig. 3 producing the truth table of NAND and NOR gates

A	B	C	Z	
0	0	0	1	<i>N</i>
0	0	1	0	<i>O</i>
0	1	0	0	<i>R</i>
0	1	1	0	
1	0	0	1	<i>N</i>
1	0	1	1	<i>A</i>
1	1	0	1	<i>N</i>
1	1	1	0	<i>D</i>

If  $A = 0$ , the MLG performs logical NOR operation. If  $A = 1$ , it performs NAND operation.

need further research. Thus, the MLG unlocks an efficient alternative technique of complete computing at room temperature using nanoscale patterned ferromagnetic materials.

The beauties of the MLG lie in the following advantages: (a) The MLG is able to perform all fundamental logical gate operations, giving an opportunity of complete computing. (b) It operates at room temperature without any extra difficulty. (c) The logic definition is identical throughout the entire computation process. (d) The MLG enables very high speed computing as it settles the output and input as fast as in 1.4 ns. (e) The MLG architecture is so simple that it needs identical Permalloy dots to be placed apart from each other. Furthermore, the following promising facts are noteworthy. The MLG is non-volatile. Considering two-dimensional dot array, an integration density of  $1.6 \text{ billion gate cm}^{-2}$  is readily achievable. Since the entire networks can be built on a single plane, three-dimensional hardware can be constructed by placing one plane on the top of each other. Further increase of the integration density is possible by reducing the dot size if permitted. The MLG will be in general very stable against temperature and will consume low power.

#### 4. Conclusion

We have presented a novel technique of achieving binary logical operations by ferromagnetic nanodots, which has been named as MLG. It is demonstrated that the MLG successfully performs fundamental logical operations. Because of the observed binary nature of the ferromagnetic nanodots, it has been used as a building block of the MLG. The MLG possesses number of advantages that enables it to meet the future demands of the increasing speed and

miniaturization. To the best of our knowledge, this is a first report of achieving fundamental logical operations by an array of ferromagnetic nanodots, and no other alternative techniques are so efficiently able to demonstrate a complete computing at room temperature.

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