Spin Electronics

Magnetic Full Adder Based on NDR-enhanced Anomalous Hall Effect

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Abstract—Spintronic logic devices have attracted attention because of the prospect of breaking the von-Neumann bottleneck through nonvolatile in-memory computing. Although varieties of spin Boolean logic gates have been proposed, spintronic arithmetic logic units such as adders have not been extensively studied because of the difficulties in application of the cascade method of CMOS-based logic in spintronic devices. Here, we experimentally demonstrated a spintronic full adder based on anomalous Hall effect and geometrical tuning magnetization switching driven by spin-orbit torque. The anomalous Hall effect of magnetic bits was enhanced by nonlinear elements with N-type negative differential resistance to control the ON/OFF state of MOSFETs which determined the write voltage of the memory unit. The magnetization of the memory bits in the memory unit were switched one by one as write voltage increased because of geometry difference. The order of magnetization switching caused the response of the anomalous Hall voltage of the memory unit to the input configurations to conform with the logic function of full adder. Computation function of full adder combined with memory writing was experimentally realized with only 7 magnetic bits and 2 steps. The reduced number of magnetic bits and time steps indicated efficiency of space and time of our device which beneficial for practical applications.

Index Terms—Spin Electronics, Electrical control of spin, Magnetic logic devices

I. INTRODUCTION

Conventional CMOS-based computer with processor built on volatile semiconductor logic elements requires frequent data transfer between CPU and external memory [Luo 2017]. As the line width of semiconductor devices shrinks, the drawback of such von-Neumann architecture in performance and power dissipation has become nonnegligible [Joshi 2020]. On one hand, the time delay on the BUS and the performance gap between processor and nonvolatile memory have limited the operation speed. On the other hand, the energy consumption in the process of data communication leads to extra power dissipation [Backus 1983, Liu 2005]. Spintronics is one of the emerging fields that have the potential to break through the von-Neumann bottleneck by combining data processing and storage within a single integrated platform [Joshi 2020, Dieny 2020]. Such prospect has motivated research on nonvolatile spintronic logic devices compatible with modern semiconductor technologies such as electric-field controlled spin logic [Li 2018, Baek 2018], magnetic logic gates based on magnetic tunnel junctions (MTJ) [Zabihi 2019], magnetic domain-wall (DW) logic [Allwood 2005, Omari 2019, Zheng 2020, Luo 2020] and reconfigurable magnetic gates based on anomalous Hall effect (AHE) enhanced by nonlinear elements [Luo 2017, Lu 2021, Pu 2020, Pu 2021]. Although varieties of spintronic Boolean logic gates have been proposed, problems still

remain in experimental demonstration of more complex computing elements such as full adder. For electric-field controlled spin logic, despite its low power consumption benefitting from the field-controlled mechanism, the current logic implementation scheme is incapable of practical computing tasks because of the poor cascading property [Li 2018, Baek 2018]. In MTJ-based magnetic logic circuits, adders and other arithmetic logic elements were constructed by cascading of NAND gates through sequential read-out and data writing of MTJs [Zabihi 2019]. Because each step of cascading would cost one clock cycle of operation time, the time efficiency of complex combinational logic functions requiring several steps of cascading was limited. DW-based combinational logic circuits perform logic functions by connecting majority gates based on propagation of DWs with networks of ferromagnetic nanowires [Luo 2020]. Although such method could cascade logic gates directly, it is not suitable for logic circuits with large scale because the operation time is limited by the speed of DW motion. AHE-based spin logic enhances the AHE of magnetic multilayers with perpendicular magnetic anisotropy (PMA) by nonlinear elements with negative differential resistance (NDR) [Luo 2017, Lu 2021, Pu 2020, Pu 2021]. Magnetic majority gates was realized by connecting three PMA in parallel, and the enhanced AHE signal was transformed into the write current of storage bits, which could serve as the input of logic gates on the next level. Thus, complex combinational logic functions such as adders were performed by cascading of majority gates. However, in such method of logic implementation where logic functions relied on interconnection of input bits, one input bit could only be used in one logic gate at the

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1 same time. The poor fan-out property increased the time delay of
2 complex logic operations. Moreover, the number of bits required
3 to complete the logic operation far exceeded the number of
4 variables in the logic operation itself, resulting in redundancy of
5 space occupation in memory for the logic operations. In order to
6 improve the fan-out property and reduce the number of magnetic
7 bits involved in logic operations, we propose here a new
8 implementation of AHE-based spin logic. A full adder combined
9 with reconfigurable Boolean logic gate covering logic operations
10 AND, OR, NAND and NOR was demonstrated experimentally.
11 Contrary to previous full adders, the inputs of our device are
12 insulated from each other and each input could be shared by
13 multiple logic gates. The number of magnetic bits needed was
14 reduced by 50% and the required clock cycle was reduced by 33%
15 compared with the previous AHE-based spintronic full adder [Pu
16 2021].

17 II. EXPERIMENT

19 The three-terminal magnetic bits in our device were fabricated
20 from magnetic multilayer Ta (3 nm)/Co₄₀Fe₄₀B₂₀ (0.7 nm)/MgO
21 (1 nm) with SiO₂ capping layer of 5 nm deposited on Si substrate
22 with 300 nm of thermally oxidized SiO₂. After sputtering (Rotaris
23 Singulus), the multilayer was annealed at 220 °C in vacuum (< 2
24 × 10⁻⁴ Pa) for 1 hour to achieve perpendicular magnetic
25 anisotropy. The magnetic bits were then patterned by UV
26 lithography and Ar-ion milling. Ti (10 nm)/Au (50 nm) was used
27 for electric contacts. Apart from the magnetic elements, other
28 components of our device including the NDR elements and
29 MOSFETs were available on the market. Measurements to
30 demonstrate the logic and memory functions of the device,
31 including electrical manipulation of magnetization direction of the
32 CoFeB layer and measuring the response of output voltage to
33 different magnetization states of input bits, were conducted using
34 Keithley 2400 and Keithley 2182A at room temperature, with the
35 external magnetic field provided by an electromagnet.

36 III. RESULT AND DISCUSSION

38 The AHE-based spintronic full adder was mainly composed of
39 two parts: logic inputs and memory unit consisted of a group of
40 parallel-connected magnetic bits with different length (Fig. 1).
41 The two parts were connected by three n-channel enhancement
42 MOSFETs and resistors.

43 The logic inputs comprised three magnetic bits and three pairs
44 of N type NDR elements (Fig. 1). The three-terminal magnetic
45 bits were fabricated from ferromagnetic multilayers
46 Ta/CoFeB/MgO with perpendicular magnetic anisotropy. Due to
47 the AHE, the voltage at the top electrode was dependent on the
48 magnetization of the magnetic bit. However, the magnitude of the
49 difference of voltage was too small for logic functions because of
50 the risk of logic errors. In our device, pairs of N type NDR
51 semiconductor elements were used to solve this problem. By
52 connecting NDR pairs to the magnetic bits (Fig. 1), positive
53 feedback was introduced to the circuit. When the magnetization of
54 the magnetic bits was upward ("0" state), the voltage between the

55 top and right electrode V_O exceeded the voltage between the left
56 and top electrode $V_{in}-V_O$. As a result, the right NDR would reach
57 the negative slope region earlier than the left NDR. In this region,
58 increase of the voltage on the NDR caused the current to decrease,
59 leading to increase of resistance. The increase of resistance would
60 lead to further increase of voltage, such positive feedback resulted
61 in a large output voltage V_{OH} . On the contrary, in the case where
62 the magnetization pointed downward ("1" state), V_O was smaller
63 than $V_{in}-V_O$ because of AHE. The left NDR would first reach
64 negative slope region and the positive feedback resulted in a large
65 $V_{in}-V_O$. Since the logic input circuit was driven by voltage source
66 V_{in} , a large $V_{in}-V_O$ indicated a low voltage output V_{OL} . As a result,
67 the NDR pair enhanced the difference between V_O and $V_{in}-V_O$
68 caused by AHE, which ensured the output ratio to be large enough
69 for logic applications (Fig. 2(a)). Detailed analysis about the
70 mechanism of N-NDR enhancement of anomalous Hall voltage
71 was performed by load-line analysis [Pu 2021]. The three-terminal
72 magnetic bit could be modelled by Δ -type resistor network
73 comprised of three resistors R_{Left}^{Eff} , R_{Right}^{Eff} and R_{Mid}^{Eff} . According to
74 Kirchhoff's Law, the voltage and current in R_{Left}^{Eff} , R_{Right}^{Eff} and the
75 NDR pair followed the equations below:

$$76 \quad I_0 = I_{in} - V_{in}/R_{Mid}^{Eff} \quad (\text{Eq. 1})$$

$$77 \quad V_{in} = V_{Left} + V_{Right} \quad (\text{Eq. 2})$$

$$78 \quad I_0 = I_{Left}^{NDR} + V_{Left}/R_{Left}^{Eff} = I_{Right}^{NDR} + V_{Right}/R_{Right}^{Eff} \quad (\text{Eq. 3})$$

79 I_0 was the current in the upper branch of the circuit (R_{Left}^{Eff} ,
80 R_{Right}^{Eff} and the NDR pair). The resistance of the resistors was
81 dependent on the magnetization of the magnetic bits because of
82 the AHE. When the magnetization was upward (downward), R_{Right}^{Eff}
83 was larger (smaller) than R_{Left}^{Eff} . Besides the equations above, the
84 current and voltage in the NDRs should also follow the I-V
85 characteristics of NDR.

$$86 \quad I_{Left(Right)}^{NDR} = I^{NDR}(V_{Left(Right)}) \quad (\text{Eq. 4})$$

87 The current and voltage of NDRs was presented by the
88 solutions of Eq. 3 and Eq. 4 which could be derived by load line
89 analysis. The N-shaped I-V curve represented the I-V
90 characteristics of NDRs and the straight lines were drawn
91 according to Eq. 3. The straight lines and the intersection points in
92 the figures were referred to as load lines and working points
93 respectively. The different slopes of the load lines were caused by
94 the magnetization-dependent resistance of R_{Left}^{Eff} and R_{Right}^{Eff} . The
95 analysis below was based on the case of magnetization upward
96 and the opposite case could be analyzed with similar method.

97 When V_{in} started to increase from zero, both working points
98 were in the positive differential resistance region of the N-shaped
99 curve and moved upward and rightward (Fig. 3(b)). Once the
100 upper load line reached the maximum point of the curve, the two
101 working points would move in different directions as V_{in}
102 continued to increase (Fig. 3(c)). At this stage, as the x
103 coordinates of the working points represented the voltage of the
104 NDRs, the separation of working points caused the difference
105 between V_{Left} and V_{Right} to increase rapidly, which could explain
106 the bifurcation V_O in Fig. 2(a). Such bifurcation enlarged the
107 magnetic response of V_O . As a result, the magnetization of input

1 bits was transformed to the magnitude of V_O with large output
2 ratio so that V_O could control the writing of the memory unit in
3 **Fig. 1**.

4 As mentioned above, when the magnetization of the input bit
5 was upward ("0" state), the output voltage V_O was in high voltage
6 state V_{OH} . On the contrary, when the magnetization of the input
7 bit was downward ("1" state), the output voltage V_O was in low
8 voltage state V_{OL} . The output voltage of input circuit served as the
9 gate voltage V_{GS} of the MOSFETs with threshold gate voltage
10 $V_{GS(TH)}$ satisfying $V_{OH} > V_{GS(TH)} > V_{OL}$. Thus, the ON/OFF state of
11 MOSFETs was determined by the magnetization of the magnetic
12 bits. Since the three input bits a, b and c respectively controlled
13 the ON/OFF states of the three MOSFETs, the write voltage V_{Write}
14 on the memory unit with three parallel-connected memory bits
15 was determined by the magnetization of input bits (**Fig. 2(b)**). The
16 experiment result showed that the value of V_{Write} was related to the
17 number of "0"s and "1"s in the three input terminals. When all
18 three inputs were "1", the output voltage V_O of all the inputs were
19 low and the MOSFETs were in the OFF state. Since the R_{DS} of
20 OFF-state MOSFETs was much larger than the resistance of the
21 memory unit, the voltage V_{Write} applied on the memory unit was
22 very low. When one of the inputs was "0", the output voltage V_O
23 was in the high voltage state V_{OH} and the MOSFET connected to
24 this input was switched ON. In this case, the write voltage V_{Write}
25 depended on the resistor R connected to the MOSFET. Since the
26 resistance of R was much smaller than R_{DS} of OFF-state MOSFET,
27 V_{Write} increased. As the number of "0"s of the inputs increased
28 from 0 to 3, the more resistors were connected in the write circuit.
29 Since V_{DD} was constant and the resistors could be considered as
30 parallel-connected, the voltage V_{Write} applied on the memory unit
31 increased stepwise since the resistors were connected in parallel
32 (**Fig. 2(b)**). Such dependency of V_{Write} on the inputs set up the
33 relation between the number of "0"s of the inputs and the write
34 voltage. Thus, the logic function of the device depended on the
35 state of memory unit under different V_{Write} .

36 The memory unit consisted of three parallel-connected
37 magnetic bits sharing the same width (W) but had different length
38 (L). According to previous work of spin-orbit torque (SOT)-
39 driven magnetization switching [Liu 2012], the charge current in
40 Ta layer of the magnetic bits generated out-of-plane spin current
41 which would switch the magnetization of the ferromagnetic
42 CoFeB layer with the assistance of a constant external magnetic
43 field colinear with the current. The critical switching current of
44 magnetization reversal driven by spin-orbit torque was related to
45 the current density J_C , which was proportional to the electric field
46 V_{Write}/L . Thus, the difference in length among the magnetic bits
47 would lead to different critical switching voltage (**Fig. 4**). The
48 opposite chirality of magnetization reversal of the magnetic bit in
49 the middle was because the magnetic bit in the middle was
50 connected inversely to the other two bits. By comparing the
51 stepwise write voltage V_{Write} (**Fig. 2b**) and the critical switching
52 voltage V_C of the memory bits (**Fig. 4**), it could be found that with
53 the number of "0"s of the inputs increased from 0 to 3, the
54 magnetization of the three bits would be reversed in sequence by
55 SOT (**Fig. 5(a)**). As a result, as the number of "0"s of the three
56 inputs increased, the memory unit experienced four different
57 magnetization states (0,1,0), (1,1,0), (1,0,0), and (1,0,1),

58 corresponding to number of "0"s of the inputs 0, 1, 2 and 3
59 respectively. When focusing on the relation between the
60 magnetization state of the middle bit and the inputs, it could be
61 found that such relation matched with 3-input majority gate,
62 which served as CARRY output (C_{Out}) of full adder.

63 In addition to the C_{Out} , the "SUM" (S) output also needed to be
64 given for a full adder. As **Fig. 5(a)** demonstrated, when the
65 number of "0"s in the three input bits a, b, and c increased from 0
66 to 3, the magnetization of the memory unit changed in the order of
67 (0,1,0), (1,1,0), (1,0,0), and (1,0,1). The change of magnetization
68 state resulted in different anomalous Hall voltage when the AHE
69 of the three magnetic bits were superimposed by connecting them
70 in parallel with the same current direction (**Fig. 5(b)**). If the
71 positive and negative value of the Hall signal were regarded as
72 logic output "1" and "0" respectively, as the number of "0"s in the
73 three input bits a, b, and c increased from 0 to 3, the output
74 changed in the sequence of ("0", "1", "0", "1"), which was
75 consistent with the truth table of the "SUM" output of a full adder.
76 Therefore, once the magnetization states of the memory unit was
77 determined by the three input bits a, b, and c, the computation
78 results of full adder including the "SUM" and "CARRY OUT"
79 were already stored in the memory unit in the form of the
80 magnetization of the middle bit and the whole memory unit
81 respectively, which indicated the completion of the computing
82 process of full adder. Moreover, the "SUM" output represented by
83 the overall anomalous Hall signal of the three magnetic bits of
84 memory unit could be rewritten into one magnetic bit, which
85 could serve as an input bit in subsequent logic operations when
86 cascade was needed. In the rewriting process, N-NDR pairs were
87 applied to enhance the output "SUM" signal (**Fig. 6(a)**), and the
88 enhanced output voltage V_{Out} was also capable of controlling the
89 ON/OFF state of a MOSFET. Hence, the write voltage V_S across
90 storage bit d (**Fig. 6(b)(c)**) was determined by the
91 magnetization state of the memory unit and the "SUM" output
92 contained in the memory unit was written into the storage bit d
93 (**Table 1**), which was ready to serve as inputs of subsequent
94 magnetic logic operations.

95 Compared with the previous full adder [Pu 2021], the full adder
96 presented above has advantages in the following three aspects.
97 Firstly, in our AHE-based spintronic full adder, the memory unit
98 played a major role in the realization of the logic functions,
99 whereas in other AHE-based devices logic functions relied on the
100 interconnection between the input bits. Such design allowed the
101 function of memory unit to be no longer limited to storage of logic
102 outputs but also in logic applications. Since the memory unit
103 shared the task of logic, it was not necessary for our logic devices
104 to use a large number of input bits to implement complex logic
105 functions. Compared with previous AHE-based full adder [Pu
106 2021], the number of magnetic bits was reduced from 14 to 7,
107 which was beneficial for decreasing the occupation of space.
108 Secondly, because of complicated cascade process, the previous
109 AHE-based full adder took three steps to accomplish an adding
110 computation. Because the inputs needed to be called repetitively
111 in the computation process, the data stored in the input bits could
112 not be changed throughout the process. As a result, the inputs
113 could only be redefined in an extra step after the computation
114 process, which was disadvantageous for time efficiency. In

1 comparison, the computation process of the proposed full adder
 2 consisted of two steps. In the first step, the magnetization of the
 3 memory unit was reversed according to the inputs, storing the
 4 output of the full adder in the memory unit. In the second step, the
 5 computation result was transferred into a single magnetic bit in
 6 convenience of cascade. During the second step the inputs could
 7 be rewritten or redirected to prepare for the next computation task
 8 assigned to the logic device allowing for pipe-line computations.
 9 The reduction of computation steps and availability of pipi-line
 10 computation indicated the advantage of our device in time
 11 efficiency. Thirdly, our device conformed well the requirements
 12 of parallel computation. As mentioned above, the logic functions
 13 of our device were performed mostly in the process of writing
 14 process where the logic input bits contributed equally and
 15 independently. Since the logic function no longer relied on the
 16 interconnection between input bits, the inputs acquired the ability
 17 of fan-out, which allowed each of them be shared by multiple
 18 logic units simultaneously. The fan-out ability of logic inputs was
 19 important for parallel computations.

20 In conclusion, by introducing geometrical design into the
 21 memory unit, we demonstrated a new nonvolatile spintronic full
 22 adder based on NDR-enhancement of AHE. The design of
 23 memory unit consisted of three magnetic bits different in length
 24 allowed the logic functions to be performed in the writing process
 25 instead of by complex interconnections of input bits. The
 26 redistribution of logic and memory function led to optimization of
 27 AHE-based full adder device in terms of space occupation, time
 28 efficiency and ability of parallel computing, indicating
 29 improvements of AHE-based spintronic logic devices aiming at
 30 practical applications.

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 93

94
 95
 96 **Fig. 1** Schematics of the spintronic full adder based on NDR-
 97 enhanced AHE. Image of the magnetic bits in optical microscope
 98 was presented. The bottom electrode of the magnetic bit was only
 99 used to measure the current-induced reversal of magnetization and
 100 was not involved in the logic operations.

Fig. 2 Response of (a) the gate voltage of MOSFETs (V_o) and (b) write voltage of memory unit (V_{Write}) to logic inputs

Fig. 3 (a) Modelling of three terminal magnetic bit by Δ -type resistor network. (b)(c) Load line analysis of the mechanism of NDR-induced enhancement of anomalous Hall voltage.

Fig. 4 Magnetization reversal of the magnetic bits in the memory unit

Fig. 5 (a) Four different magnetization states of memory unit with different logic inputs. (b) Anomalous Hall effect of the memory unit at the four magnetization states.

Fig. 6 (a) Read-out and rewriting circuit of “SUM” output. (b)(c) NDR-enhanced anomalous Hall voltage (V_{Out}) and write voltage of bit d (V_S) corresponding to different magnetization of memory unit. The NDR pair enhanced the AHE of the memory unit to control the write voltage V_S on bit d so that the “SUM” output was rewritten into bit d for subsequent logic operations.

Table 1 Magnetization of Bit d under different logic inputs

Inputs (a,b,c)	V_{Out} (V)	V_S (V)	Magnetization of Bit d
(1,1,1)	2.08	2.99 (1)	1(↓)
(1,1,0)			
(1,0,1)	0.08	$\sim 10^{-5}$ (0)	0(↑)
(0,1,1)			
(1,0,0)			
(0,1,0)	2.08	2.99 (1)	1(↓)
(0,0,1)			
(0,0,0)	0.08	$\sim 10^{-5}$ (0)	0(↑)