Realization of Complete Boolean Logic Functions using a Single Memtranstor

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A memtranstor that directly correlates charge (q) and magnetic flux (φ) via the nonlinear magnetoelectric effects is considered as the fourth memelement in addition to the memristor, memcapacitor, and meminductor. Just like the well-known memristor, the memtranstor also holds a great potential for developing advanced electronic devices such as nonvolatile memory and artificial synapses. Complete Boolean logic functions can be implemented in a single memtranstor made of the $Fe_{0.81}Ga_{0.19}/[Pb(Mg_{1/3}Nb_{2/3})O_3]_{0.7}[PbTiO]_{0.3}/Fe_{0.81}Ga_{0.19}$ multiferroic heterostructure. There are four variables in a memtranstor: the initial state, the input electric potentials of two terminals, and the phase angle. By assigning different values to the four variables, 16 complete Boolean logic functions are demonstrated in experiments using a single memtranstor. The sign of the magnetoelectric voltage of the device is considered as logic output. The concurrence of nonvolatile memory and complete Boolean logic functions makes the memtranstor a promising candidate for future computing systems beyond von Neumann architecture.

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I. INTRODUCTION

The development of information technology puts forward higher requirements for information storage and computing capabilities of computers. The traditional von Neumann architecture that separates the logic and memory units is becoming a bottleneck to further improve the performance of computers because of the interconnect delays due to the transfer of data from the memory circuit to the logic circuit [1]. Therefore, there is strong interest in developing future computing systems with logic-in-memory architecture where memory and logic functions are integrated in a single device. To this end, many nonvolatile devices such as the memristor [2–9], phase change memory (PCM) [10–12], and magnetic tunneling junctions [13–16] have been used to implement logic functions in the past decades.

As the fourth fundamental circuit element, the transtor is a two-terminal device defined by the relationship between charge (q) and magnetic flux (φ) [17]. Its counterpart memelement, called a memtranstor, is characterized by nonlinear hysteresis loops between q and φ. The q-φ relationship in these devices is based on the magnetoelectric (ME) effects [18], that is, magnetic field control of electric polarization and electric field control of magnetization. As demonstrated experimentally [19], the ME effects in the memtranstor yield a relationship between ΔP and ΔH, which can be converted into the $\Delta q{\sim}\Delta\varphi$ relationship. In the memtranstor, the quantity called transtance ($T = dq/d\varphi$) can be switched between positive and negative or high and low by external fields. The value of transtance is usually represented by the ME voltage (V_{ME}) in practical devices. Just like the memristor [6–9] and memcapacitor [20], the memtranstor also has great potential for developing nonvolatile information devices. In our previous studies, the memtranstor has been successfully used to implement nonvolatile memory [21–23] and nonvolatile logic gates [24] as well as artificial synapse devices [25]. The advantages of the memtranstor rely on its simple sandwich structure, which is good for fabrication, its low energy consumption in writing (comparable to that of ferroelectric memories), and its nondestructive parallel reading.

In a recent study, we realized nonvolatile NOR and NAND Boolean logic functions in a memtranstor made of a $Ni/[Pb(Mg_{1/3}Nb_{2/3})O_3]_{0.7}[PbTiO_3]_{0.3}/Ni$ multiferroic structure [24]. However, functional completeness and computation complexity are two important criteria to

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evaluate the performance of a logic methodology. Functional completeness indicates that one Boolean logic set can be used to express all possible truth tables by only using members of the set [26]. {NOR} and {NAND} are two well-known complete binary Boolean logic sets. NAND and NOR can assemble into any Boolean logic functions. For example, the XOR gate can be realized by connecting four NAND gate $p \cdot \bar{q} + \bar{p} \cdot q = \overline{\overline{p \cdot \overline{p \cdot q}} \cdot \overline{q \cdot \overline{p \cdot q}}}$. Thus, multiple devices are required to implement other Boolean logic functions. In computer science, the computational complexity is the amount of required resources to realize the computation [27]. The resources can be simply understood as the number of logic gates and operation steps. Therefore, it requires significant computational complexity to realize other Boolean logic functions using NAND or NOR gates. In this work, we intend to realize complete Boolean logic functions in a single memtranstor, which will greatly reduce the computational complexity while keeping the functional completeness.

II. EXPERIMENTS

The memtranstor prepared in this work is made of the $Fe_{0.81}Ga_{0.19}/[Pb(Mg_{1/3}Nb_{2/3})O_3]_{0.7}[PbTiO_3]_{0.3}/Fe_{0.81}Ga_{0.19}$ (FeGa/PMN-PT/FeGa) sandwich structure with in-plane magnetic moment (M) and out-of-plane electric polarization (P) as shown in Fig. 1(a). The FeGa binary alloy (galfenol) is an excellent material to fabricate a memtranstor because of its large magnetostrictive coefficient, low saturation magnetic field, and low cost [28,29]. PMN-PT is a well-known commercial ferroelectric material with a high piezoelectric coefficient [30]. Thus, the memtranstor will produce significant ME coupling effects through interfacial strain between the magnetic and ferroelectric layers. More importantly, the FeGa/PMN-PT/FeGa memtranstor shows a large ME voltage around zero dc magnetic field (H_{dc}), which is known as the self-bias effect [31–33]. This is good for practical applications because no dc bias magnetic field is required.

The FeGa/PMN-PT/FeGa memtranstor is prepared by magneton sputtering two FeGa layers on the surface of a PMN-PT ($2 \times 5 \times 0.2$ mm^3) single crystal substrate with (110)-cut. The thickness of the FeGa layer is 500 nm and the top and bottom FeGa layers act as magnetic layers and electrodes. In this work, this large device is used to demonstrate the principle of complete Boolean logic functions. We note that the device size can be easily scaled down by nanofabrication for practical applications.

A typical dynamic technique is used to measure the ME voltage. A small ac magnetic field H_{ac} (phase angle α)

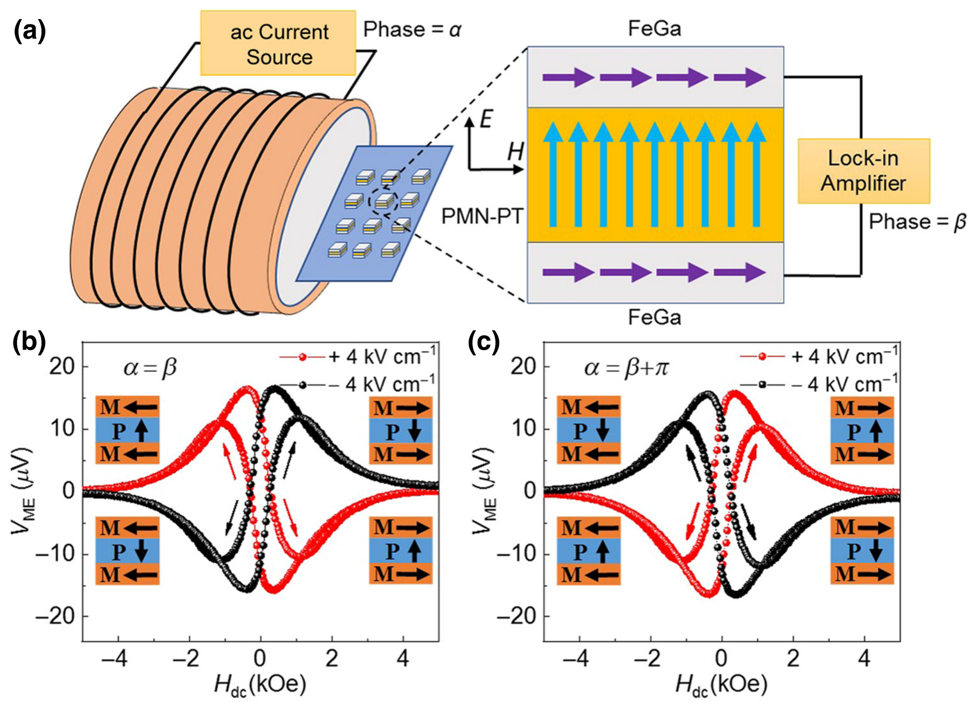


FIG. 1. Structure and principle of the memtranstor. (a) The structure of the FeGa/PMN-PT/FeGa memtranstor with in-plane magnetization in the FeGa layer and out-of-plane polarization in the PMN-PT layer. The array of memtranstors is placed into a read solenoid, which generates an ac magnetic field (H_{ac}) with phase angle α. The ME voltage is detected by a lock-in amplifier with reference phase angle β. The arrows represent directions of positive E and H. (b),(c) The ME voltage as a function of dc bias magnetic field after positive (red) and negative (black) poling. The H_{ac} is 1 Oe with a frequency of 10 kHz. The phase angle is set to $\alpha = \beta$ in (b) and $\alpha = \beta + \pi$ in (c), respectively. The sign of the ME voltage can be controlled by selecting the direction of polarization as well as the phase angle.

with a frequency of 10 kHz is generated through a solenoid driven by a Keithley 6221 ac current source. Meanwhile, the inductive voltage on the device by H_{ac} is picked up by using a Stanford Research SR830 lock-in amplifier with a reference phase angle β. To switch the electric polarization of PMN-PT, an electric field pulse is applied by using a Keithley 6517B source meter. The device is placed in the Oxford TeslatronPT superconducting magnet system to apply an in-plane dc magnetic field. All the measurements are performed at room temperature.

III. RESULTS AND DISCUSSION

Figure 1(b) shows the measured ME voltage as a function of H_{dc} when the phase angles α and β are set to be identical ($\alpha = \beta$). The memtranstor is fully poled under an electric field of $-4\,\mathrm{kV\,cm^{-1}}$ before measuring the ME voltage. When P is set downward (black line), the ME voltage gradually increases from zero to the maximum (approximately 16.5 μV) with the H_{dc} sweeping from 5 to 0.4 kOe. The ME voltage reaches the minimum (approximately -11 μV) at -1 kOe and gradually returns to zero when H_{dc} is swept to -5 kOe. When the magnetic field is scanned from negative to positive, the ME voltage reaches the minimum (approximately -16.5 μV) at -0.4 kOe and the maximum (approximately 11 μV) at 1 kOe. The ME voltage remains at a high level of about ± 11.5 μV at zero magnetic field due to the self-bias effect. The ME voltage is reduced to zero at ± 5 kOe because the magnetization of FeGa is saturated at high magnetic fields and the magnetostrictive coefficient is close to zero. In contrast, when P is set upward (red line), the sign of the ME voltage is totally opposite, being negative in positive H_{dc} and positive in negative H_{dc}. For comparison, Fig. 1(c) shows the ME voltage measured with the phase angle $\alpha = \beta + \pi$. The sign of the ME voltage becomes exactly opposite to the case of $\alpha = \beta$.

We use a lock-in amplifier to read the ME voltage as shown in Fig. 1(a). A lock-in amplifier is a widely used instrument to detect small ac signals [34]. The ME signal $[V_{sig}\sin(\omega_s t + \alpha)]$ is multiplied by the lock-in reference signal $[V_L \sin(\omega_L t + \beta)]$ and produces two sine waves

$$\begin{aligned} V &= V_{sig} V_L \sin(\omega_s t + \alpha)\sin(\omega_L t + \beta) \\ &= \tfrac{1}{2} V_{sig} V_L \cos[(\omega_S - \omega_L)t + \alpha - \beta] \\ &\quad - \tfrac{1}{2} V_{sig} V_L \cos[(\omega_S + \omega_L)t + \alpha + \beta], \end{aligned} \tag{1}$$

where V_{sig} and V_L are the magnitudes of the ME signal and lock-in reference signals, and ω_S, ω_L, α, and β are the frequencies and phase angles. The ME signal has the same frequency and phase angle as the H_{ac} and ac current source. The output signal will be $V = \frac{1}{2} V_{sig} V_L \cos(\alpha - \beta)$ after the multiplied signal passes through a low pass filter of the lock-in amplifier. Thus, the output ME voltage depends on the phase difference between α and β, which provides an extra parameter to control the output states of the device. For $\alpha = \beta$ and $\alpha = \beta + \pi$, the ME signals are opposite, as shown in Figs. 1(b) and 1(c).

We first test the function of nonvolatile memory based on the memtranstor. As shown in Figs. 2(a) and 2(b), the ME voltage of the device can be switched between positive and negative by applying $\pm 4\,\mathrm{kV\,cm^{-1}}$ E-field pulses with 10-ms widths. The role of the applied electric pulse is to reverse the electric polarization so that the ME coefficient changes its sign. In this kind of device, the ME coupling is caused by the interfacial strain between the magnetic and ferroelectric layers. The ME voltage can be described by the following equation

$$V_{ME} \propto \frac{dP}{dH} = \frac{dP}{d\lambda}\frac{d\lambda}{dH}, \tag{2}$$

where λ is the strain, $dP/d\lambda$ is the piezoelectric coefficient, and $dH/d\lambda$ is the magnetostriction coefficient. When the direction of P is reversed, the piezoelectric coefficient becomes opposite, which leads to the switching of the ME voltage.

In principle, the memtranstor can work at a much faster speed because the microscopic mechanism is the switch of the ferroelectric domains by applying an E field. The ME voltage retains its state for a long time after removing the electric pulse, showing excellent retention behavior. Thanks to the self-bias effect of the FeGa/PMN-PT/FeGa memtranstor, all the above measurements are performed under zero dc bias magnetic field. In addition, the memtranstor shows a good endurance. The ME voltage

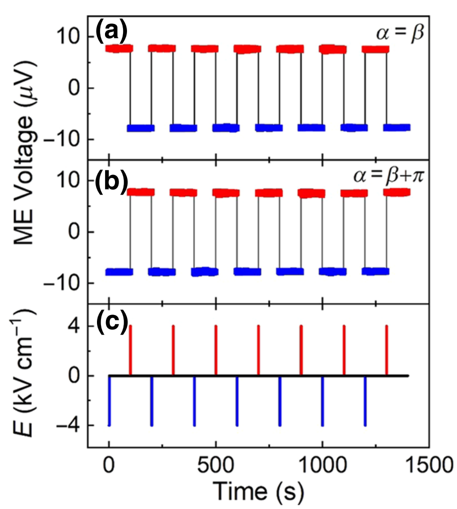
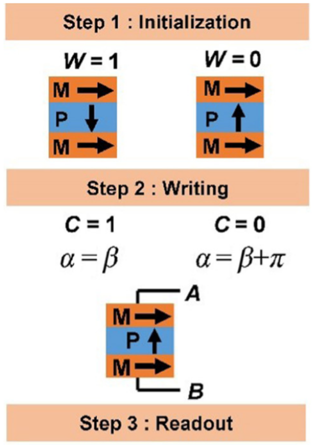


FIG. 2. Two-level nonvolatile memory based on the FeGa/PMN-PT/FeGa memtranstor. (a),(b) Repeatable switch of the ME voltage between positive and negative in a zero bias magnetic field with phase angles $\alpha = \beta$ and $\alpha = \beta + \pi$, respectively. (c) The sequence of E-field pulses. After applying a $\pm 4\,\mathrm{kV\,cm^{-1}}$ pulse with a 10-ms width to reverse electric polarization, the ME voltage is measured for 100 s.

(a)



(b)

	Logic 1	Logic 0
W	P↓	P↑
A	2 kV cm⁻¹	−2 kV cm⁻¹
B	2 kV cm⁻¹	−2 kV cm⁻¹
C	α = β	α = β+π

(c)

Name	Logic	W	A	B	C
Null	0	p	q	q	$\bar{p}$
Identity	1	p	q	q	p
Transfer	p	q	0	1	p
Transfer	q	1	0	p	q
Complement	$\bar{p}$	q	1	0	p
Complement	$\bar{q}$	0	1	p	q
AND	$p\cdot q$	p	1	q	1
NAND	$\bar{p}+\bar{q}$	0	$\bar{p}$	q	0
OR	$p+q$	1	p	q	q
NOR	$\bar{p}\cdot\bar{q}$	p	0	q	0
Implication	$\bar{p}+q$	1	p	q	1
Implication	$p+\bar{q}$	0	p	q	0
Inhibition	$\bar{p}\cdot q$	0	p	q	1
Inhibition	$p\cdot\bar{q}$	p	q	0	1
Exclusive-OR	$\bar{p}\cdot q+p\cdot\bar{q}$	0	p	1	q
Equivalence	$p\cdot q+\bar{p}\cdot\bar{q}$	0	0	p	q

FIG. 3. Principle of logic operation using a memtranstor. (a) The operation sequence to realize logic functions. There are three steps to complete a logic function: initialization, writing, and read-out. Four parameters are used in these three steps. (b) The assignment table for the four parameters. Each parameter only has two choices, which represent two logic inputs "1" and "0." (c) The assignment for the four parameters in each of the 16 Boolean logic functions.

does not show any sign of decay after 10^3 cycles (see Fig. S1 in the Supplemental Material [35]).

The completely opposite behavior of the ME voltage shown in Figs. 2(a) and 2(b) is due to the difference in phase angle. When the phase angle is set from $\alpha = \beta$ [Fig. 2(a)] to $\alpha = \beta + \pi$ [Fig. 2(b)], the sign of the ME voltage reverses, becoming positive after the $+4\,\text{kV cm}^{-1}$ electric pulse and negative after the $-4\,\text{kV cm}^{-1}$ electric pulse. Therefore, there are three ways to control the sign of the ME voltage. First, when α equals β, the ME voltage can be switched from positive (negative) to negative (positive) by applying electric pulses to reverse the direction of electric polarization. Second, one can switch the sign of the ME voltage by changing the phase angle from $\alpha = \beta$ to $\alpha = \beta + \pi$. Third, the ME voltage can be changed from positive to negative by applying a magnetic field to reverse the direction of magnetization (Fig. 1). These characteristics of the memtranstor provide a solution for realizing complete logic operations in a single device.

Previous studies have suggested that four logic variables are necessary in order to implement complete logic through mathematical equations [6–9]. In fact, there are four variables to control the output of the ME voltage of the memtranstor: the initial state, the electric fields of two terminals, and the phase angle, which are defined as W, A, B, and C, respectively.

There are three steps to perform a logic operation in the memtranstor. As shown in Fig. 3(a), the first step is "initialization": the ME voltage is set to positive ($W = 1$) by applying a $-4\,\text{kV cm}^{-1}$ E field pulse or negative ($W = 0$) by applying a $+4\,\text{kV cm}^{-1}$ pulse. The second step is "writing," which involves three variables. C representing the phase angle is defined as $C = 1$ for $\alpha = \beta$ and $C = 0$ for $\alpha = \beta + \pi$. A and B representing the electric fields applied on two terminals of the memtranstor are defined as $A, B = 1$ for $+2\,\text{kV cm}^{-1}$ and $A, B = 0$ for $-2\,\text{kV cm}^{-1}$. When $A = B$, the electric field on the memtranstor is zero, and thus the ME voltage remains in the initial state; when $A \neq B$, the electric field on the memtranstor is either +4 or $-4\,\text{kV cm}^{-1}$, and the ME voltage could be changed or not depending on the initial state. The final step is "read-out" in which the ME voltage is measured. The sign of the ME voltage represents the output of logic operations, positive as "1" and negative as "0."

As mentioned above, $W = 1$ means a positive ME voltage. There are two ways to switch the ME voltage from positive to negative. First, applying a $+4\,\text{kV cm}^{-1}$ E pulse ($A \cdot \bar{B} = 1$) to the device while keeping the phase angle $\alpha = \beta$ unchanged ($C = 1$). Second, applying a zero or $-4\,\text{kV cm}^{-1}$ E pulse ($\overline{A \cdot \bar{B}} = 1$) and changing the phase angle to $\alpha = \beta + \pi$ ($C = 0$). Similarly, when $W = 0$, we can set $\bar{A} \cdot B = 1, C = 1$ or $\overline{\bar{A} \cdot B} = 1, C = 0$ to change the negative ME voltage to positive. Thus, we can use the following equation to describe the relationship between logic output L and four input variables

$$L = W \cdot \overline{(A \cdot \bar{B} \cdot C + \overline{A \cdot \bar{B}} \cdot \bar{C})} + \bar{W} \cdot (\bar{A} \cdot B \cdot C + \overline{\bar{A} \cdot B} \cdot \bar{C}) \quad (3)$$

By assigning different values to the four variables, we can realize all 16 Boolean logic gates as listed in Fig. 3(c).

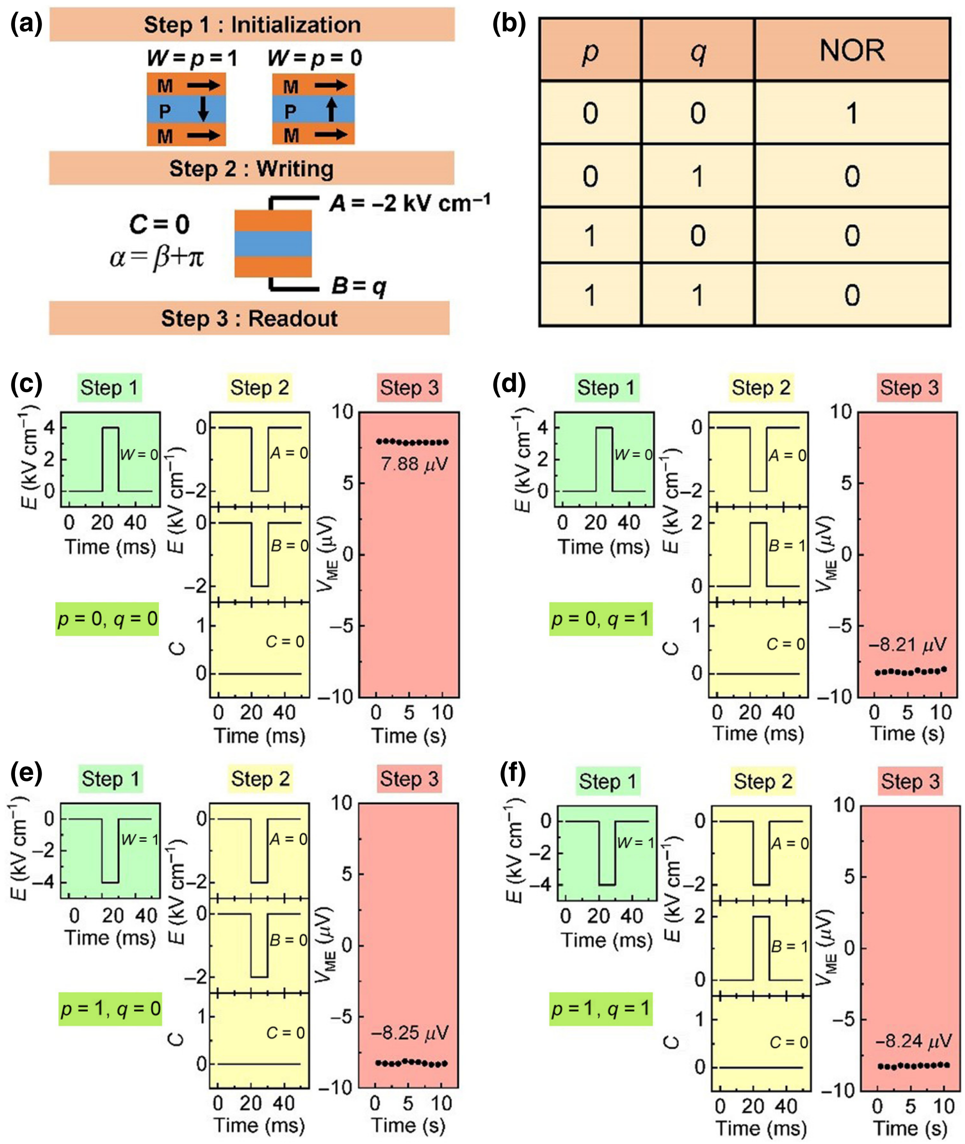


FIG. 4. Implementation of NOR function using the FeGa/PMN-PT/FeGa memtranstor. (a) The operation sequence to realize NOR logic function. A and C are preset to 0, W and B are two logic inputs. (b) The truth table of NOR operation. (c)–(f) Experimental results for four computing processes of NOR operation. The lines in step 1 and step 2 represent the applied electric field pulses in the initialization and writing steps. The dot lines in step 3 are read-out of the ME voltage of the memtranstor. Positive and negative ME voltages are regarded as logic 1 and 0, respectively.

p and q are two input variables of Boolean logic gates. It is worth noting that the nonvolatile result of the last operation can be used as the initial state of the next cycle. For logic null and NAND, they can be realized by assigning W, A, B, C to p, q, q, $\bar{p}$ and 0, $\bar{p}$, q, 0, respectively. The $\bar{p}$ is employed as an input, which is also used in other work [5,7]. It is convenient to implement by adding an inverter before the logic device. The inputs of the other 14 logic functions are simple. Here, we use the NOR logic function as an example to prove the principle of the logic operation using the memtranstor.

NOR is a universal Boolean logic gate where the output is always 0 except when the inputs are both logic 0, for which the output is 1. According to Fig. 3(c), the four variables W, A, B, and C are assigned to p, 0, q, 0, respectively. p and q represent two inputs. $A=0$ and $C=0$ means that the electric field of one terminal is $-2\,\mathrm{kV\,cm^{-1}}$ and the phase angle is $\alpha=\beta+\pi$. The operation process is shown in Fig. 4(a). Figure 4(b) shows the truth table of NOR.

The experimental results obtained for the FeGa/PMN-PT/FeGa memtranstor are shown in Figs. 4(c)–4(f). The function of NOR logic is fully realized. In Fig. 4(c), $W=p=0$ and $B=q=0$, which means that the initialization is to set the ME voltage to negative and the electric field of another terminal is also $-2\,\mathrm{kV\,cm^{-1}}$. In this case, the electric field on the memtranstor is zero and the ME voltage should not change. However, the phase angle is $\alpha=\beta+\pi$ ($C=0$) so that the ME voltage is reversed from negative to positive. Finally, the logic output is 1.

In Fig. 4(d), $W=p=0$ and $B=q=1$, which means that the initialization is to set the ME voltage to negative and the electric field of another terminal is $+2\,\mathrm{kV\,cm^{-1}}$. In this case, the electric field on the memtranstor is $-4\,\mathrm{kV\,cm^{-1}}$, which is able to reverse the electric polarization so that the ME voltage is switched from negative to positive. As the phase angle is $\alpha = \beta + \pi$ ($C = 0$), the final ME voltage changes from positive to negative. Thus, the logic output is 0. In Fig. 4(e), $W = p = 1$ and $B = q = 0$, which means that the initialization is to set the ME voltage to positive and the electric field of another terminal is set to $-2\,\mathrm{kV\,cm^{-1}}$. In this case, the electric field on the memtranstor is zero and the ME voltage remains unchanged. Since the phase angle is $\alpha = \beta + \pi$ ($C = 0$), the final ME voltage is changed from positive to negative. Therefore, the logic output is 0. In Fig. 4(f), $W = p = 1$ and $B = q = 1$, which means that the initialization is to set the ME voltage to positive and the electric field of another terminal is set to $+2\,\mathrm{kV\,cm^{-1}}$. In this case, the electric field on the memtranstor is $-4\,\mathrm{kV\,cm^{-1}}$ and the ME voltage remains positive. Since the phase angle is $\alpha = \beta + \pi$ ($C = 0$), the final ME voltage changes from positive to negative. Thus, the logic output is 0.

The above experimental results clearly demonstrate the function of NOR logic in a single memtranstor. Furthermore, the 15 other Boolean logic operations are also realized by assigning suitable values as listed in Fig. 3(c). The experimental results are presented in the Supplemental Material (Figs. S2–S16) [35]. There are five essential characteristics for a device to perform Boolean logic [36]. The complete set of Boolean logic gates are realized in the memtranstor. The binary input and output states make the memtranstor meet the "nonlinearity" requirements. "Gain" is ensured because the V_{ME} (output) is induced by the H_{ac} supplied by an independent reading coil. As the V_{ME} (output) is not able to change the states of the memtranstor and has no effect on the phase angle, the requirement of "feedback elimination" is also met in the memtranstor. As for "concatenability," the V_{ME} (output) can act as A and B to another logic gate through a voltage amplifier. In addition, the concatenability of input C (lock-in phase) can be implemented by an independent phase switcher that transforms positive or negative voltage to a 0° or 180° phase angle.

IV. CONCLUSION

The memtranstor that employs the nonlinear ME effects provides a promising route for developing nonvolatile electronic devices. In addition to the nonvolatile memory, we implement all 16 Boolean logic functions in a single memtranstor made of the FeGa/PMN-PT/FeGa multiferroic heterostructure. The initial state, the electric potentials of two terminals, and the phase angle are used as four variables in logic operations. The realization of complete Boolean logic functions in a single device would greatly increase device density and significantly improve computing efficiency. Furthermore, the memtranstor as logic gates inherits its advantages as a memory device: a simple sandwich structure for low cost and easy fabrication, high speed and energy efficiency in the writing process, as well as parallel mode in reading. The concurrence of nonvolatile memory and Boolean logic functions makes the memtranstor a potential candidate as elements for computing systems beyond von Neumann architecture.

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