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(54) **ZERO-POWER PROGRAMMABLE MEMORY CELL**

6,489,806 B1 * 12/2002 Mehta et al. 326/46

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365/185.29; 365/185.24

(58) **Field of Classification Search** 365/185.28,
365/185.24, 185.23, 185.22, 185.18, 185.29
See application file for complete search history.

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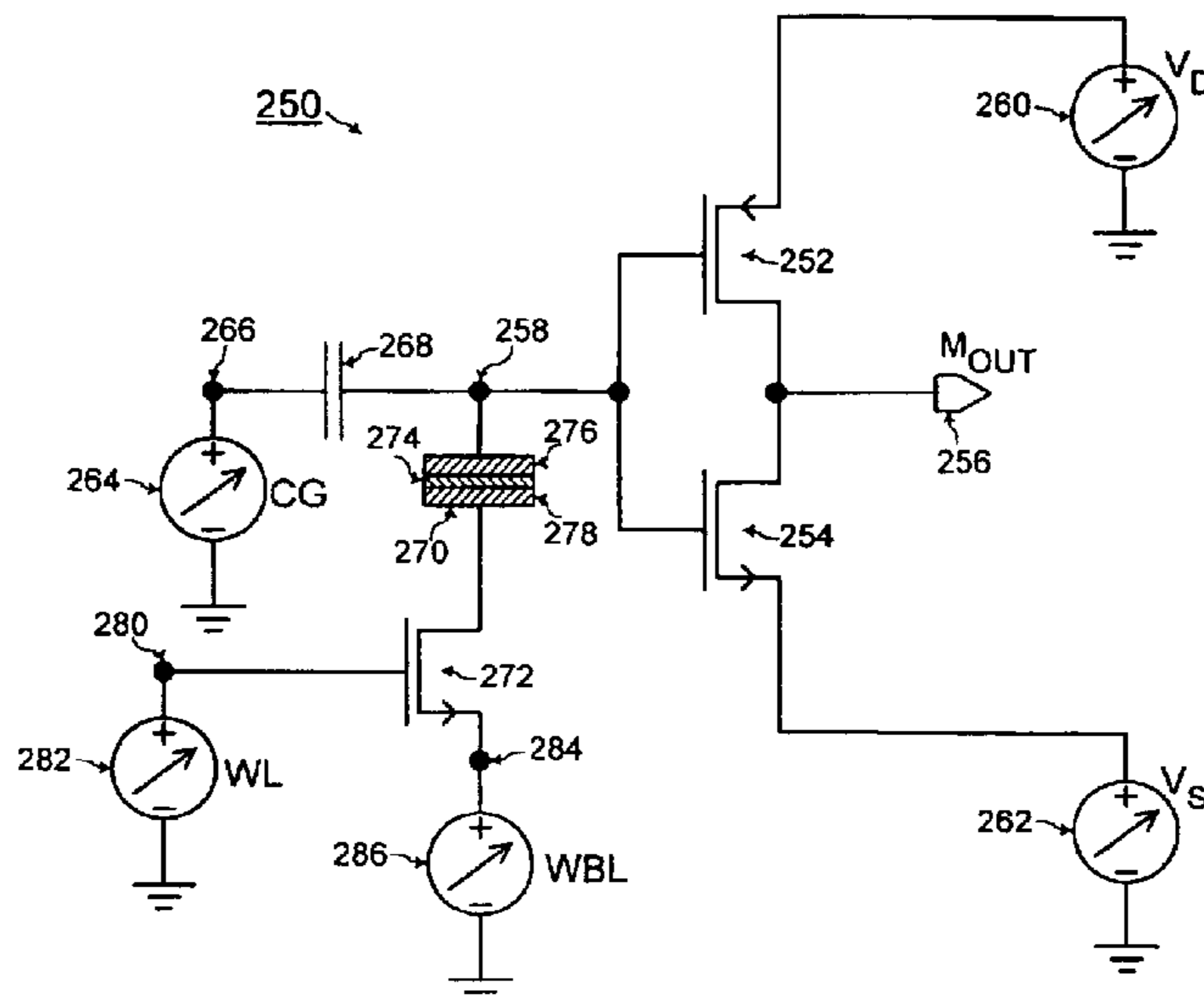
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Assistant Examiner—Hien N Nguyen

(57) **ABSTRACT**

A zero-power electrically erasable and programmable memory cell is implemented in CMOS (complementary metal oxide semiconductor) technology. A P-channel sense transistor has a source coupled to a first voltage generator, and an N-channel sense transistor has a source coupled to a second voltage generator. The drains of the P-channel and N-channel sense transistors are coupled together to form an output of the memory cell, and the gates of the P-channel and N-channel sense transistor are coupled together to form a floating gate of the memory cell. In an example embodiment of the present invention, each of the first and second voltage generators are variable voltage generators that apply a positive voltage at the respective source of each of the P-channel and N-channel sense transistors during the erase operation and/or that apply a ground or negative voltage at the respective source of each of the P-channel and N-channel sense transistors during the program operation. In another embodiment of the present invention, a magnitude of the respective threshold voltage of each of the P-channel and N-channel sense transistors is higher than a magnitude of a threshold voltage of standard process P-channel and N-channel transistors. With such a higher threshold voltage, the P-channel and N-channel sense transistors do not erroneously turn on to dissipate power during the read operation, to ensure that the memory cell is a zero-power memory cell.

37 Claims, 12 Drawing Sheets



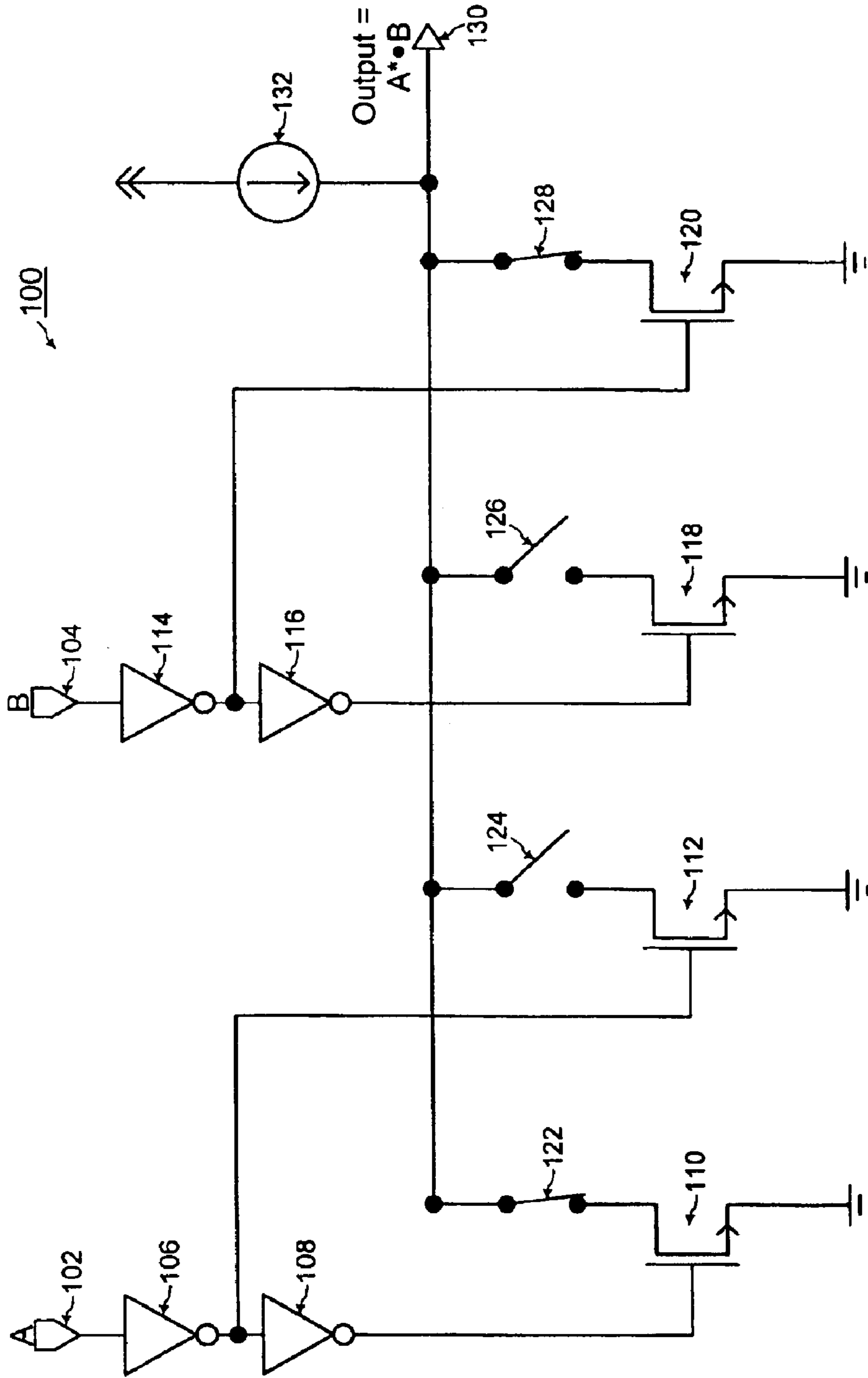


FIG. 1 (Prior Art)

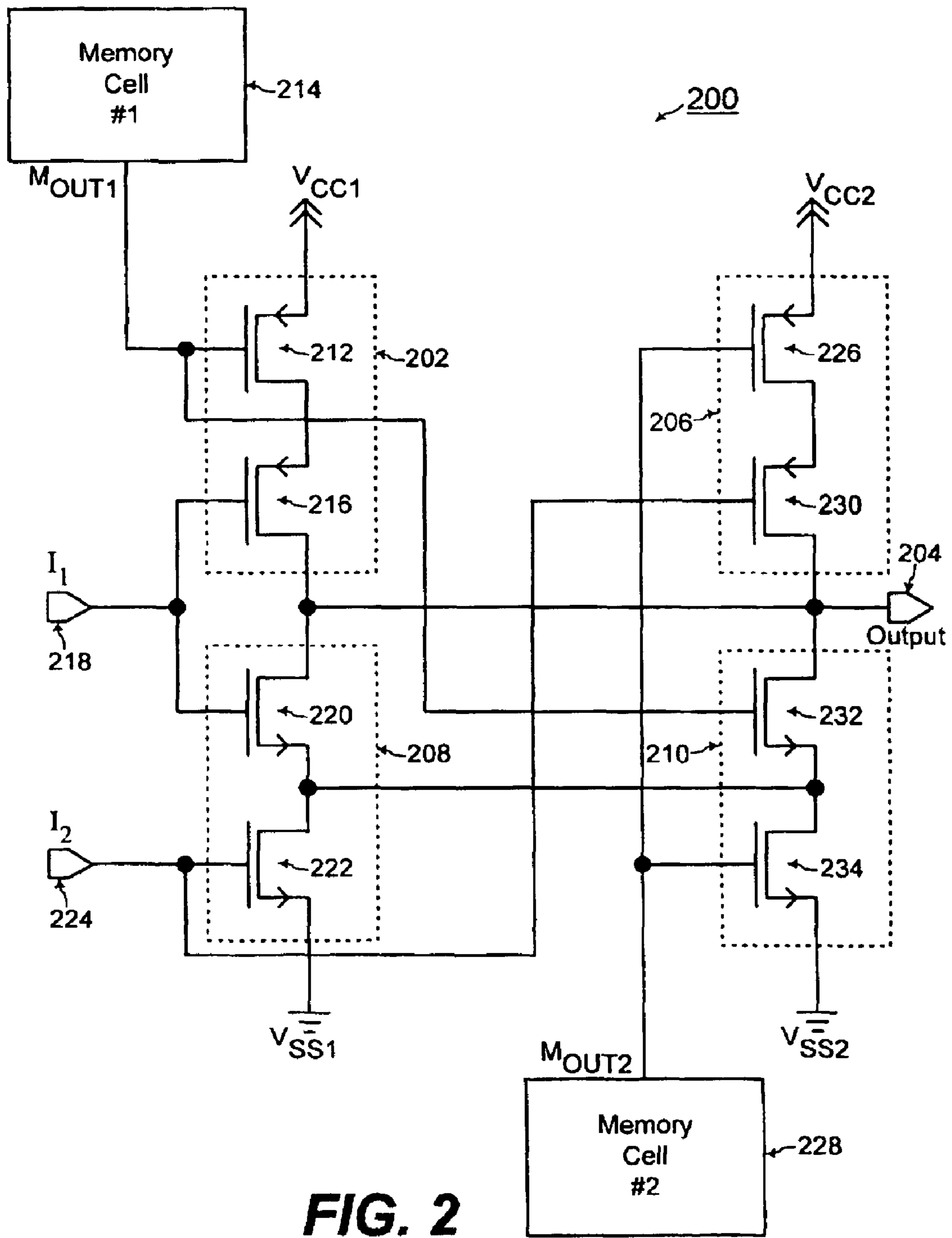


FIG. 2

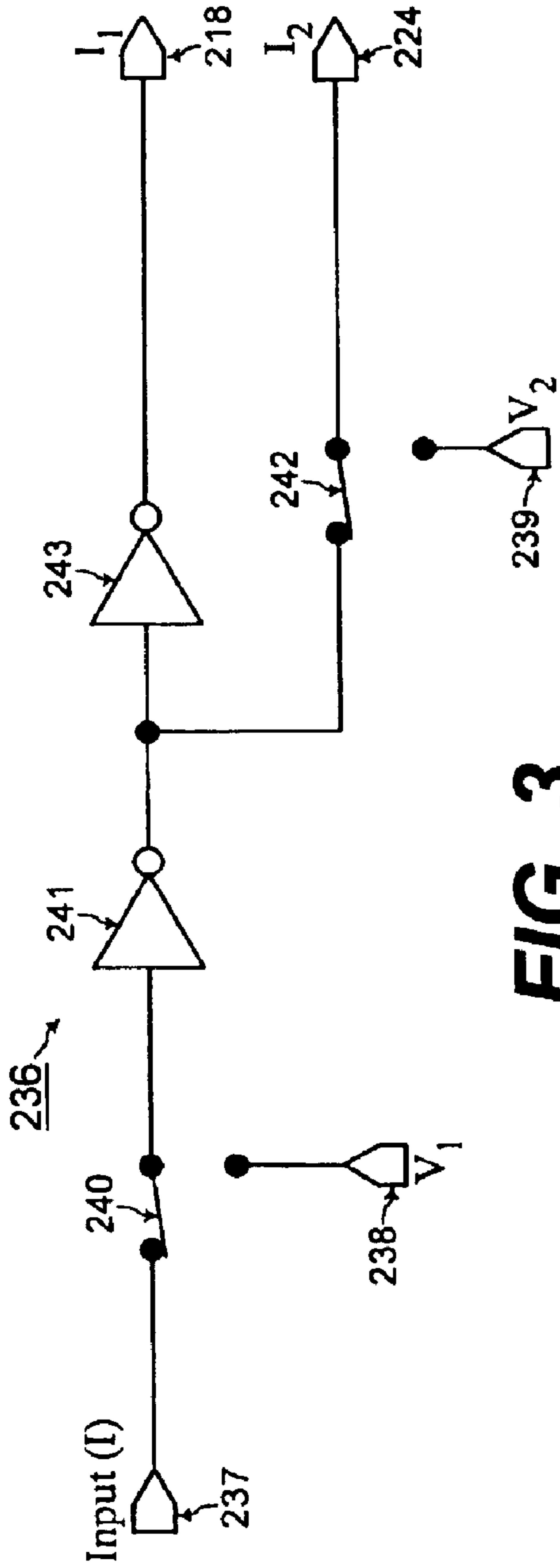


FIG. 3

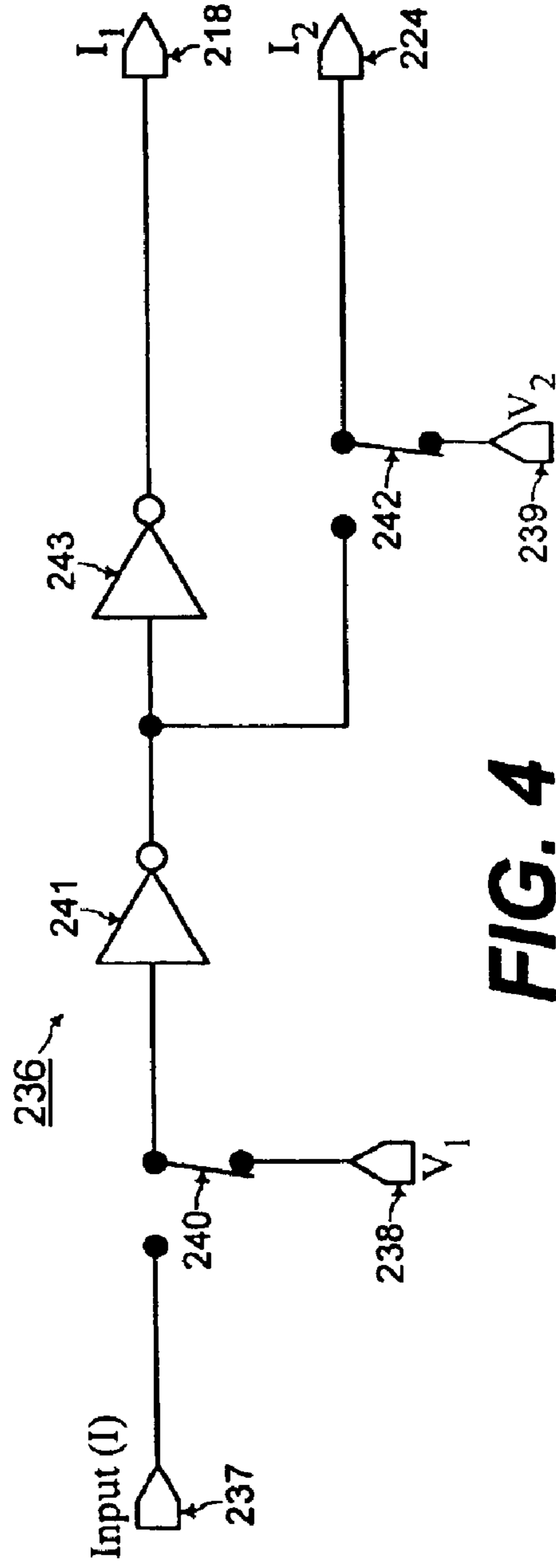


FIG. 4

I_1	I_2	M_{OUT1}	M_{OUT2}	Output
0	0	0	0	1
0	0	0	1	1
0	0	1	0	1
0	0	1	1	0
0	1	0	0	1
0	1	0	1	1
0	1	1	0	0
0	1	1	1	0
1	0	0	0	1
1	0	0	1	0
1	0	1	0	1
1	0	1	1	0
1	1	0	0	0
1	1	0	1	0
1	1	1	0	0
1	1	1	1	0

244

251

FIG. 5

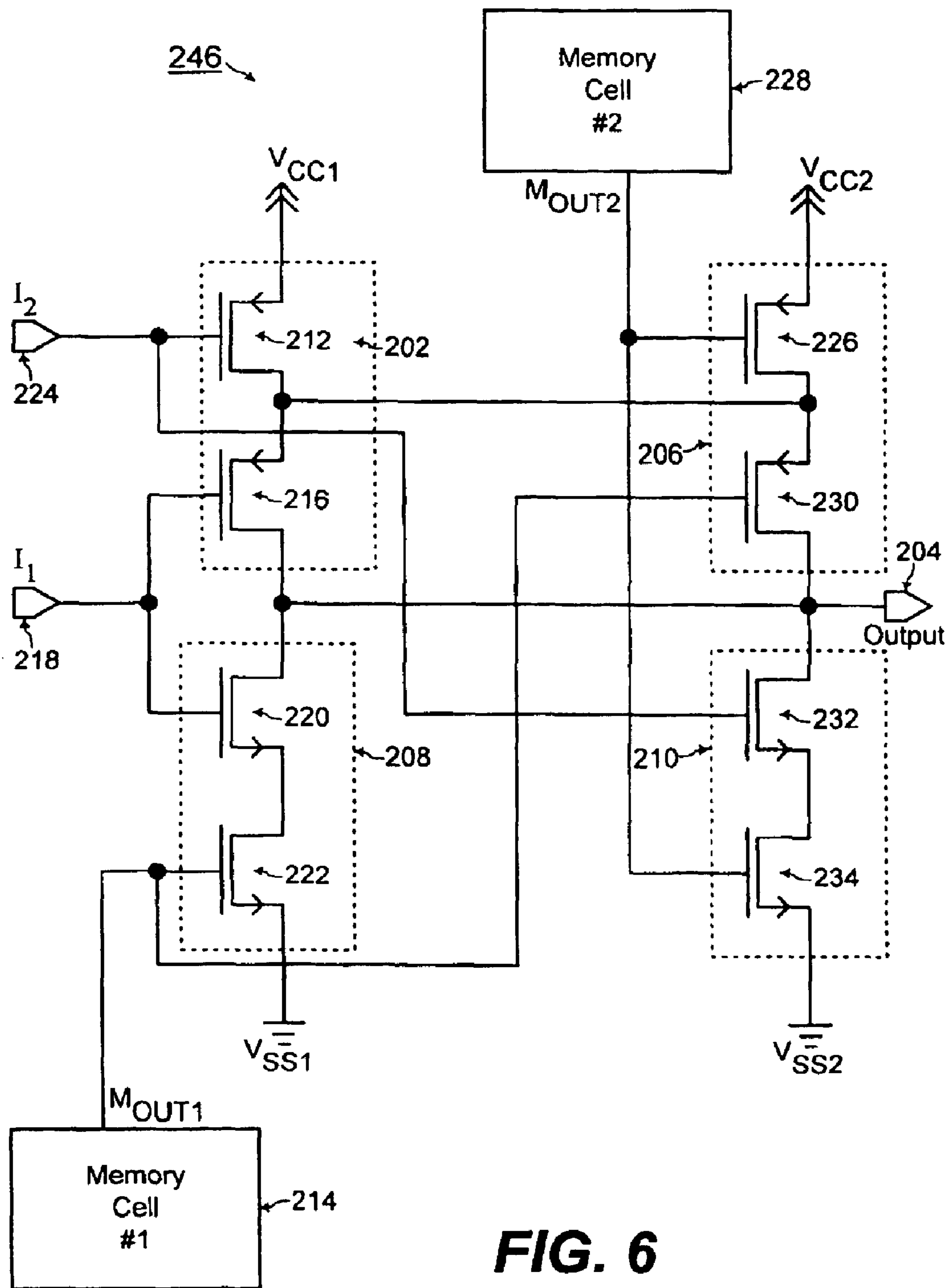


FIG. 6

I_1	I_2	M_{OUT1}	M_{OUT2}	Output
0	0	0	0	1
0	0	0	1	1
0	0	1	0	1
0	0	1	1	1
0	1	0	0	1
0	1	0	1	0
0	1	1	0	1
0	1	1	1	0
1	0	0	0	1
1	0	0	1	1
1	0	1	0	0
1	0	1	1	0
1	1	0	0	1
1	1	0	1	0
1	1	1	0	0
1	1	1	1	0

253

248

FIG. 7

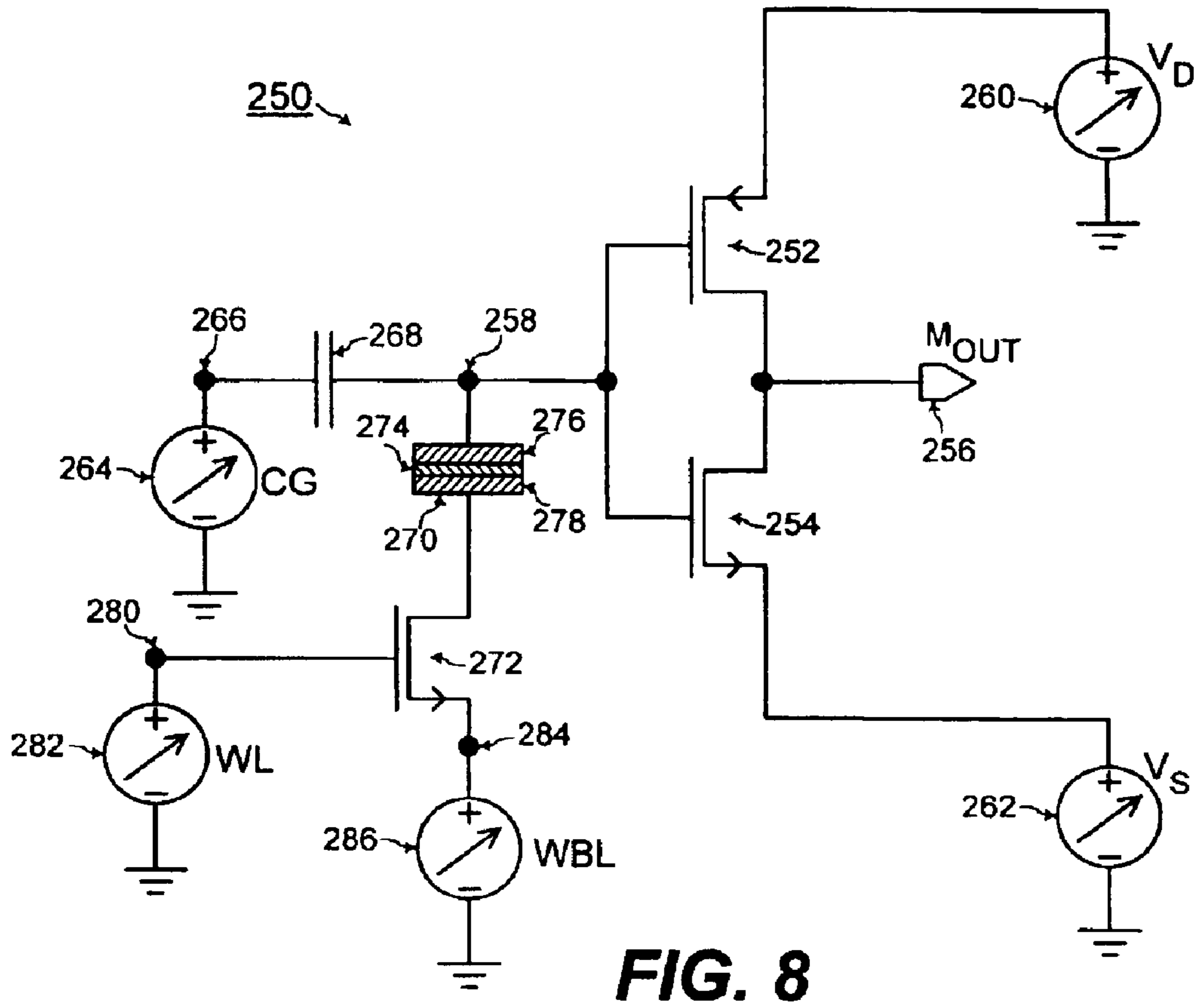
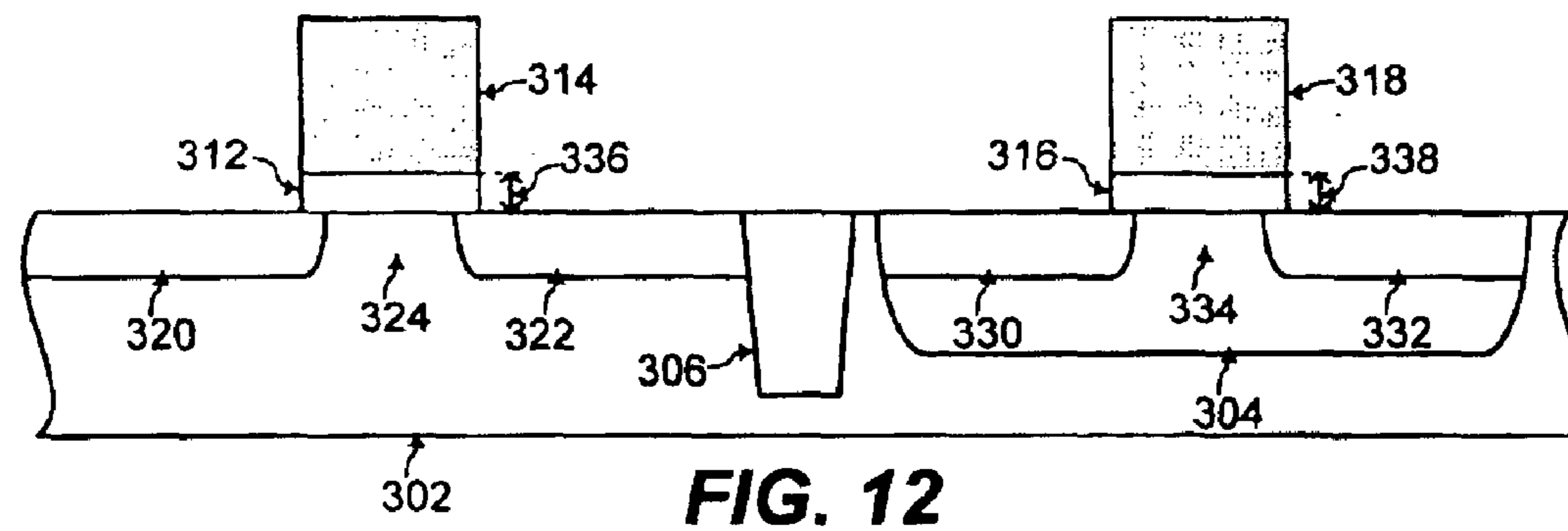
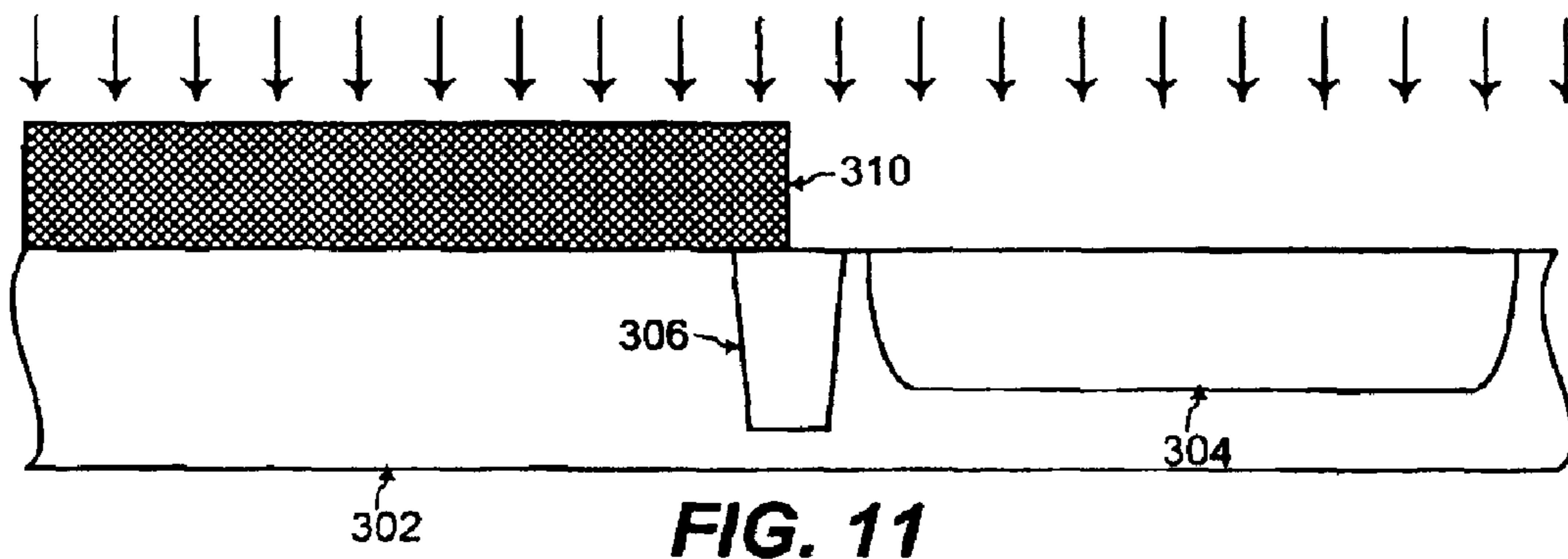
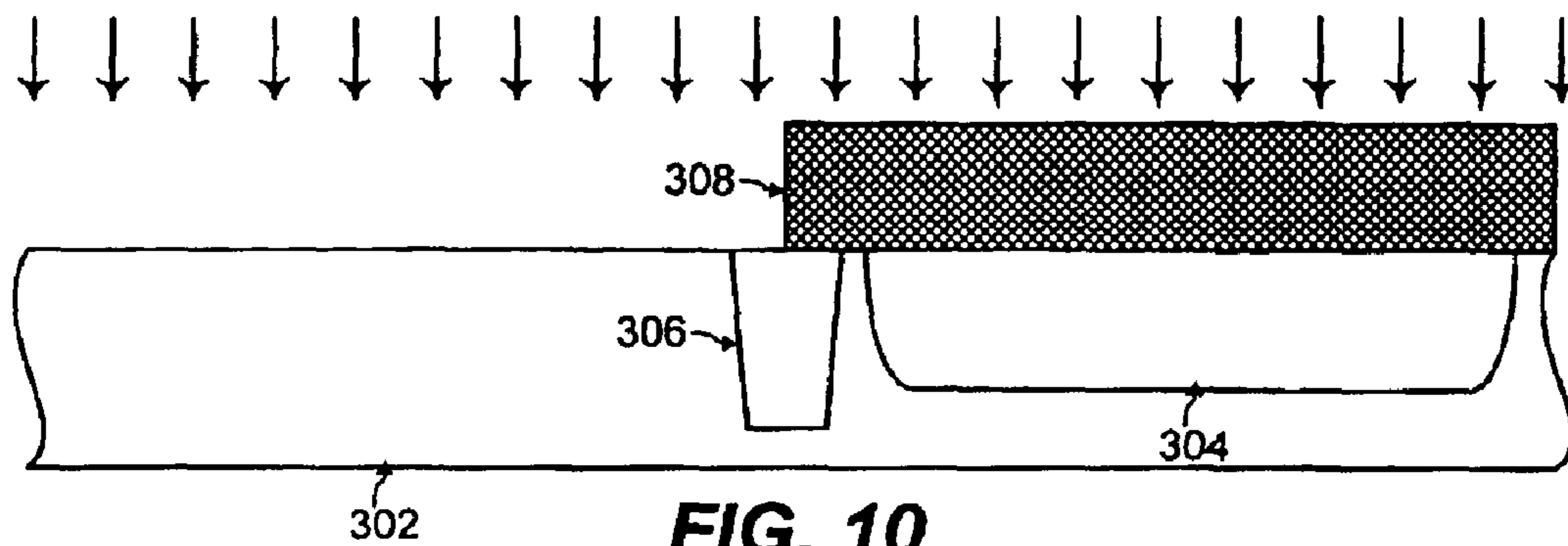


FIG. 8

Operation	CG	WL	WBL	V _D	V _S	M _{OUT}
Erase	V _{pp+} =12V	V _{dd} =1.8V	0V	V _{dd} =1.8V	V _{dd} =1.8V	V _{dd} =1.8V
Program	0V	V _{pp+} =12V	V _{pp} =11V	0V	0V	0V
Read	0.9V	V _{dd} =1.8V	0.9V	V _{dd} =1.8V	0V	V _{dd} or 0V

FIG. 9



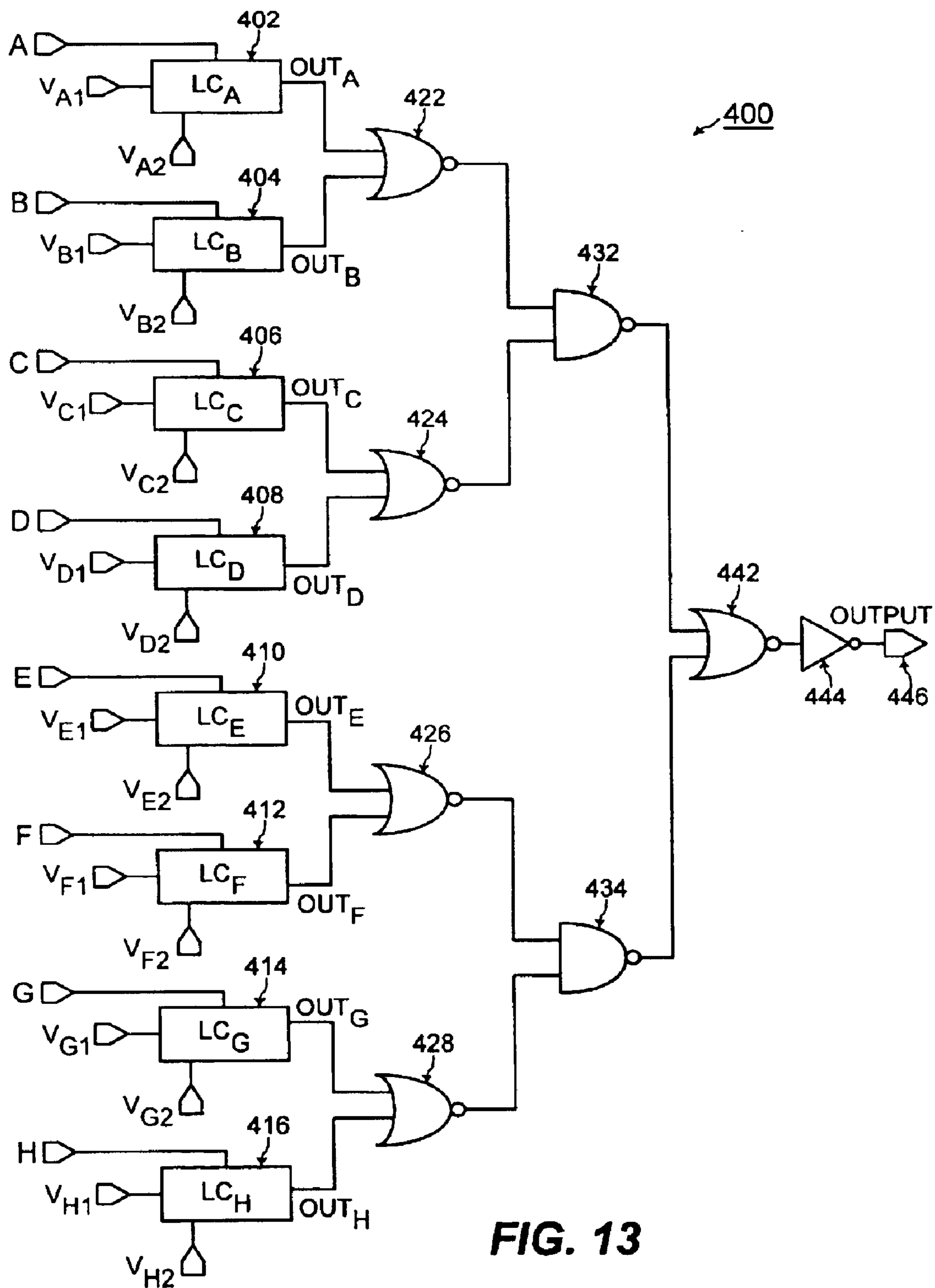


FIG. 13

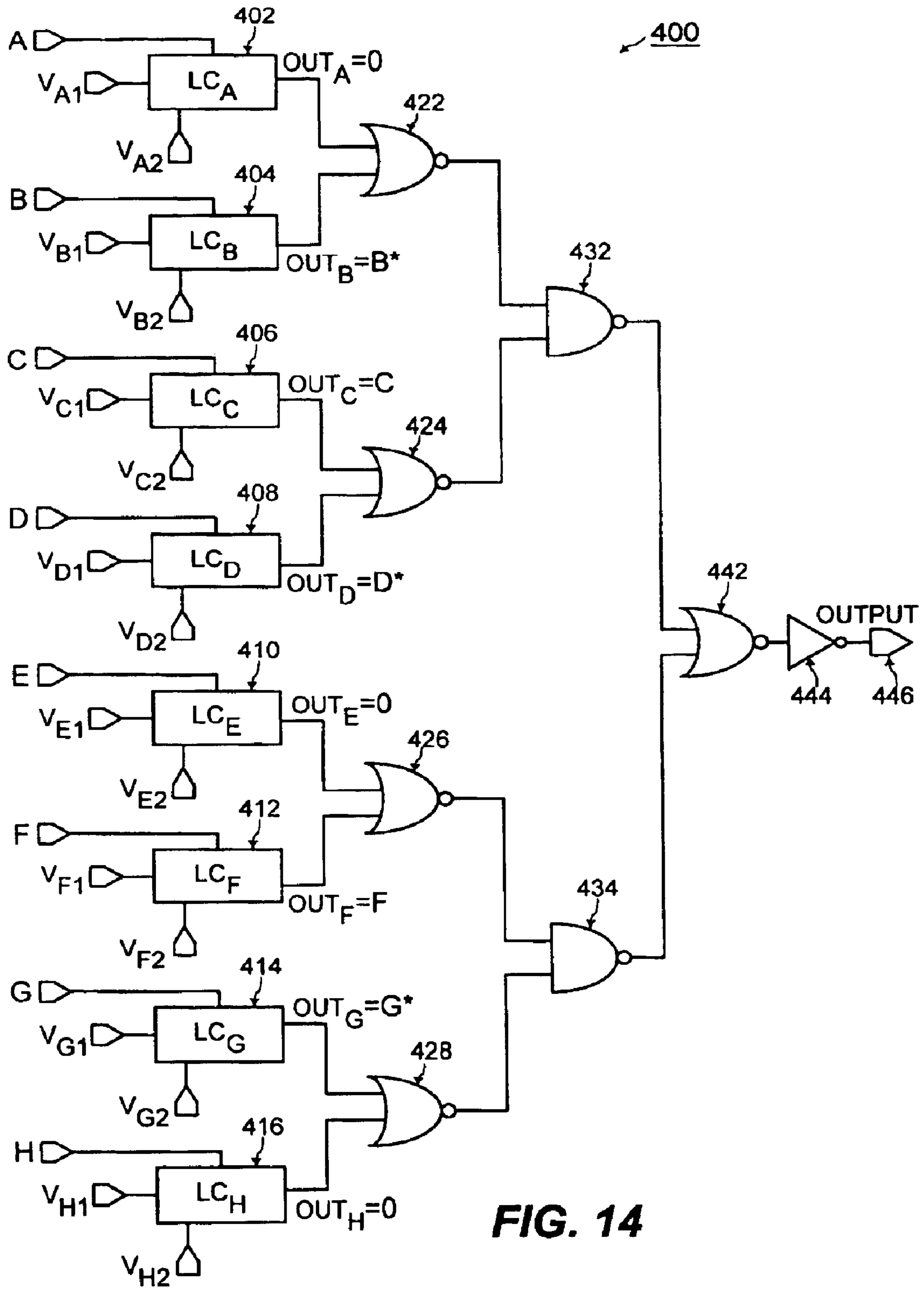


FIG. 14

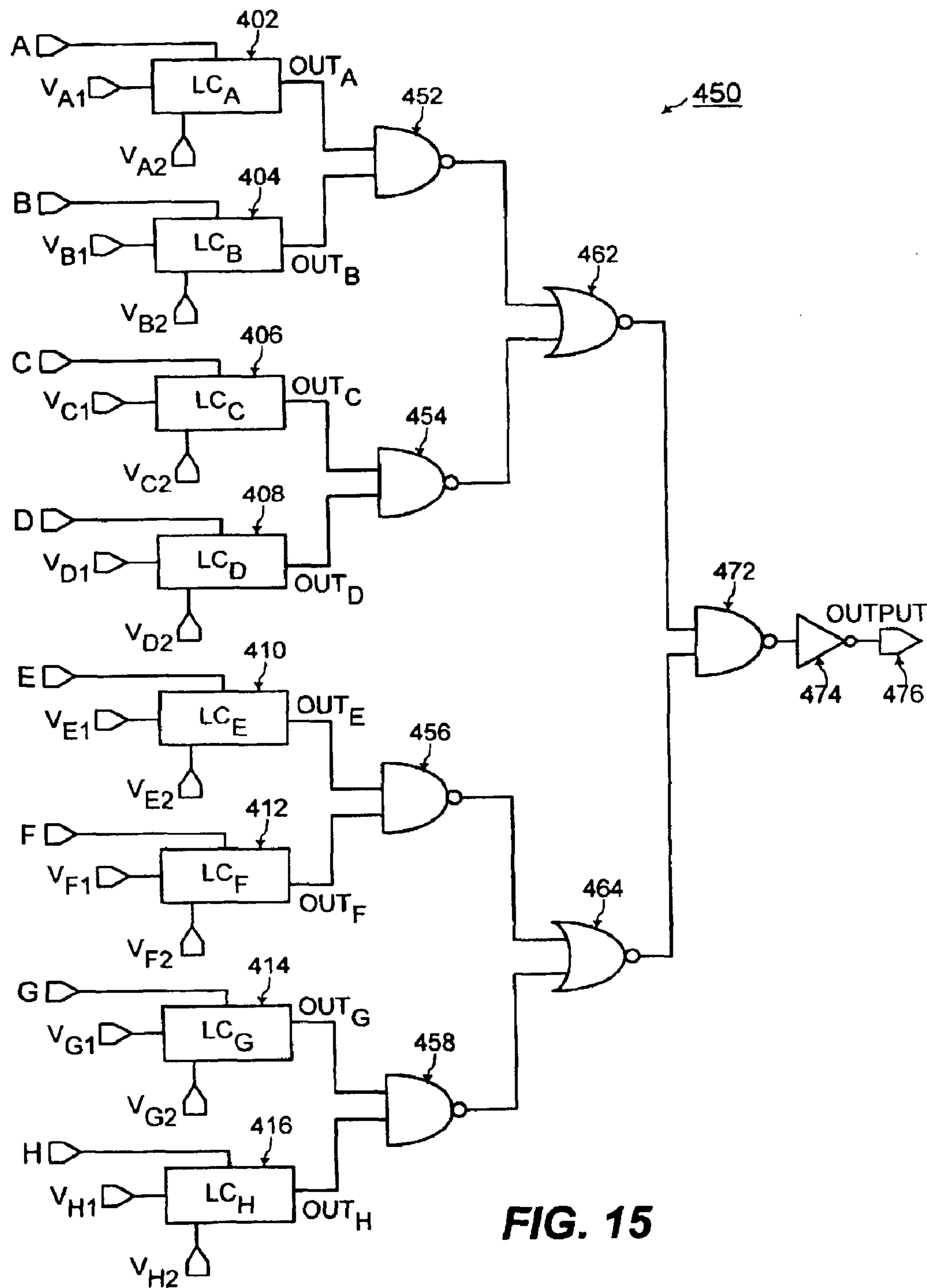


FIG. 15

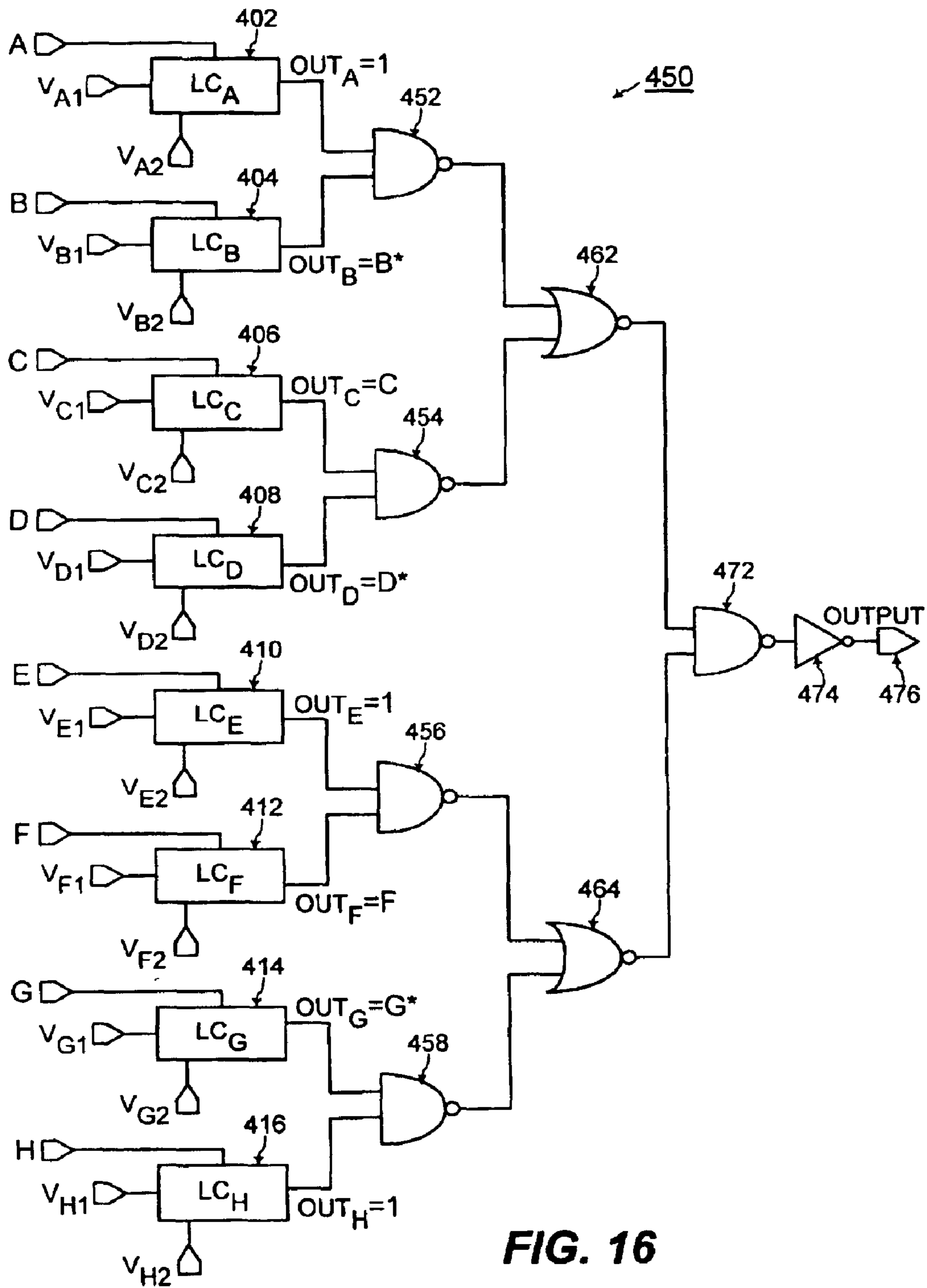


FIG. 16

ZERO-POWER PROGRAMMABLE MEMORY CELL

Matter enclosed in heavy brackets [] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to non-volatile memory devices, and more particularly, to zero-power electrically erasable and programmable memory cells, such as EEPROM cells.

2. Discussion of the Related Art

Referring to FIG. 1, an example programmable logic device is a programmable AND gate 100 of the prior art. The programmable AND gate 100 includes a first input node 102 for inputting a first input signal, A, and a second input node 104 for inputting a second input signal B. The first input signal, A, is coupled through a first inverter 106 and a second inverter 108 to the gate of a first NMOSFET (N-channel metal oxide semiconductor field effect transistor) 110. The complement of the first input signal, designated as A*, (i.e., the output of the first inverter 106) is coupled to the gate of a second NMOSFET (N-channel metal oxide semiconductor field effect transistor) 112.

Similarly, the second input signal, B, is coupled through a third inverter 114 and a fourth inverter 116 to the gate of a third NMOSFET (N-channel metal oxide semiconductor field effect transistor) 118. The complement of the second input signal, designated as B*, (i.e., the output of the third inverter 114) is coupled to the gate of a fourth NMOSFET (N-channel metal oxide semiconductor field effect transistor) 120.

A first programmable switch 122 is coupled between the drain of the first NMOSFET 110 and an output node 130, and a second programmable switch 124 is coupled between the drain of the second NMOSFET 112 and the output node 130. Similarly, a third programmable switch 126 is coupled between the drain of the third NMOSFET 118 and the output node 130, and a fourth programmable switch 128 is coupled between the drain of the fourth NMOSFET 120 and the output node 130. In addition, a current source 132 is coupled to the output node 130 for charging the output node 130 when the output signal at the output node 130 turns to a logical high state.

For operation of the programmable AND gate 100 of FIG. 1, the first, second, third, and fourth switches 122, 124, 126, and 128 are programmable to be switched open or closed. One of the first and second programmable switches 122 and 124 is programmed to be open, and the other is programmed to be closed. Similarly, one of the third and fourth programmable switches 126 and 128 is programmed to be open, and the other is programmed to be closed.

The output node 130 of the programmable AND gate 100 provides an AND operation (of one of the first input signal, A, or the complement of the first input signal A*, and one of the second input signal, B, or the complement of the second input signal, B*). If the first switch 122 is programmed to be closed with the second switch 124 being programmed to be open, then the programmable AND gate 100 provides an AND operation with the complement of the first input signal, A*, instead of the first input signal, A. On the other hand, if the first switch 122 is programmed to be open with the

second switch 124 being programmed to be closed, then the programmable AND gate 100 provides an AND operation with the first input signal, A, instead of the complement of the first input signal, A*.

Similarly, if the third switch 126 is programmed to be closed with the fourth switch 128 being programmed to be open, then the programmable AND gate 100 provides an AND operation with the complement of the second input signal, B*, instead of the second input signal, B. On the other hand, if the third switch 126 is programmed to be open with the fourth switch 128 being programmed to be closed, then the programmable AND gate 100 provides an AND operation with the second input signal, B, instead of the complement of the second input signal, B*.

Thus, in the example illustration of FIG. 1, since the first switch 122 is programmed to be closed while the second switch 124 is programmed to be open, the programmable AND gate 100 provides an AND operation with the complement of the first input signal, A*, instead of the first input signal, A. Also, since the third switch 126 is programmed to be open, while the fourth switch 128 is programmed to be closed, the programmable AND gate 100 provides an AND operation with the second input signal, B, instead of the complement of the second input signal, B*.

Thus, the output node 130 provides an output signal = A*.B. Referring to FIG. 1, only in the case when the first input signal, A, is a logical low state and the second input signal, B, is a logical high state, all of the first, second, third, and fourth NMOSFETs 110, 112, 118, and 128 do not conduct current away from the output node 130. Thus, the current from the current source 132 charges up the output node 130 to a logical high state in that case. For any other logical states of the first and second input signals, A and B, at least one of the first NMOSFET 110 and the fourth NMOSFET 120 conducts current out of the output node 130 to couple the output node 130 to ground such that a logical low state is formed at the output node 130.

In the prior art programmable AND gate 100 of FIG. 1, a constant amount of current from the current source 132 is dissipated when at least one of the first NMOSFET 110 and the fourth NMOSFET 120 conducts current out of the output node 130 to couple the output node 130 to ground. Such constant current flow results in disadvantageous power dissipation. In addition, device dimensions are constantly scaled down with advancement of IC (integrated circuit) technology. However, as supply voltages are further scaled down along with device dimensions, the noise margin of the prior art programmable AND gate 100 of FIG. 1 disadvantageously decreases to deteriorate the performance of the AND gate 100. In addition, the steady state current of the current source 132 does not necessarily scale down with device dimensions such that the prior art programmable AND gate 100 of FIG. 1 still has disadvantageous steady state power dissipation even with scaling down of device dimensions.

Thus, a mechanism is desired for implementing programmable logic devices such as programmable AND gates and programmable OR gates with minimized static power dissipation and with further scalability of device dimensions and supply voltages.

SUMMARY

Accordingly, in a general aspect of the present invention, a zero-power electrically erasable and programmable memory cell is implemented in CMOS (complementary metal oxide semiconductor) technology. Such a zero-power

electrically erasable and programmable memory cell may advantageously form part of programmable logic devices such as programmable AND, OR, NAND, or NOR gates with minimized static power dissipation.

According to a general embodiment for an electrically erasable and programmable zero-power memory cell, a P-channel sense transistor has a source coupled to a first voltage generator, and an N-channel sense transistor has a source coupled to a second voltage generator. A drain of the P-channel sense transistor is coupled to a drain of the N-channel sense transistor to form an output of the memory cell, and a gate of the P-channel sense transistor is coupled to a gate of the N-channel sense transistor to form a floating gate of the memory cell. In addition, a write transistor has a source coupled to a WBL (write bit line) and has a gate coupled to a WL (write line). A tunneling capacitor is coupled between the floating gate of the memory cell and a drain of the write transistor, and a coupling capacitor is coupled between a CG (control gate) node and the floating gate of the memory cell.

The CG (control gate) node is biased with a positive voltage during an erase operation, and the WBL (write bit line) and the WL (write line) are biased to turn on the write transistor such that a negative voltage forms on the floating gate of the memory cell by charge tunneling through the tunneling capacitor. In that case, the P-channel sense transistor turns on for forming a logical high state at the output of the memory cell during the erase operation. Alternatively, the CG (control gate) node is biased with a ground of negative voltage during a program operation, and the WBL (write bit line) and the WL (write line) are biased to turn on the write transistor such that a positive voltage forms on the floating gate of the memory cell by charge tunneling through the tunneling capacitor. In that case, the N-channel sense transistor turns on for forming a logical low state at the output of the memory cell during the program operation.

In an example embodiment of the present invention, each of the first and second voltage generators are variable voltage generators that apply a positive voltage at the respective source of each of the P-channel and N-channel sense transistors during the erase operation and/or that apply a ground or negative voltage at the respective source of each of the P-channel and N-channel sense transistors during the program operation.

In another embodiment of the present invention, a magnitude of the respective threshold voltage of each of the P-channel and N-channel sense transistors is higher than a magnitude of a threshold voltage of standard process P-channel and N-channel transistors. For example, a sum of a magnitude of a respective threshold voltage of the P-channel sense transistor and a magnitude of a respective threshold voltage of the N-channel sense transistor is greater than a minimum value in a range of a difference of a first voltage generated by the first voltage generator and a second voltage generated by the second voltage generator during a read operation of the memory cell. In that case, the thickness of the respective gate oxide for each of the P-channel and N-channel sense transistors is for a high voltage MOSFET, and the concentration of the respective channel doping for each of the P-channel and N-channel sense transistors is for a low voltage MOSFET. With such a higher threshold voltage, the P-channel and N-channel sense transistors do not erroneously turn on to dissipate power during the read operation, to ensure that the memory cell is a zero-power memory cell.

The zero-power electrically erasable and programmable memory cell is implemented in CMOS (complementary

metal oxide semiconductor) technology when the P-channel sense transistor is comprised of a PMOSFET (P-channel metal oxide semiconductor field effect transistor), and when the N-channel sense transistor and the write transistor are comprised of NMOSFETs (N-channel metal oxide semiconductor field effect transistors).

In this manner, the zero-power electrically erasable and programmable memory cell of the present invention is implemented in CMOS technology without use of any current source. Rather, the electrically erasable and programmable memory cell of the present invention operates to provide logic levels with zero power dissipation. In addition, the electrically erasable and programmable memory cell implemented in CMOS technology in the present invention is further scalable.

These and other features and advantages of the present invention will be better understood by considering the following detailed description of the invention which is presented with the attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a programmable AND gate implemented with programmable switches and a current source, according to the prior art;

FIG. 2 shows a circuit diagram representation of a zero-power logic cell implemented in CMOS (complementary metal oxide semiconductor) technology, according to a first embodiment of the present invention;

FIG. 3 shows a block diagram of an input signal selection circuit for switching a logic cell input signal and the complement of the logic cell input signal as first and second input signals to a zero-power logic cell during a functional mode, according to an embodiment of the present invention;

FIG. 4 shows the block diagram of the input signal selection circuit of FIG. 3 for switching a first logic state for the first input signal and a second logic state for the second input signal to a zero-power logic cell with the first input signal being independent of the second input signal during a verify mode, according to an embodiment of the present invention;

FIG. 5 shows a truth table of the output signal at the output node of the first embodiment of the zero-power logic cell of FIG. 2;

FIG. 6 shows a circuit diagram representation of a zero-power logic cell implemented in CMOS (complementary metal oxide semiconductor) technology, according to a second embodiment of the present invention;

FIG. 7 shows a truth table of the output signal at the output node of the second embodiment of the zero-power logic cell of FIG. 6;

FIG. 8 shows a circuit diagram representation of an electrically erasable and programmable zero-power memory cell implemented in CMOS (complementary metal oxide semiconductor) technology, according to a second embodiment of the present invention;

FIG. 9 shows a truth table for the operation of the electrically erasable and programmable zero-power memory cell of FIG. 8, according to an embodiment of the present invention;

FIGS. 10, 11, and 12 show cross-sectional views for illustrating a respective channel doping and a respective gate oxide thickness for each of the P-channel and N-channel sense transistors of the electrically erasable and programmable zero-power memory cell of FIG. 8, according to an embodiment of the present invention;

FIG. 13 shows a programmable OR gate comprising a plurality of logic cells with each logic cell having the circuit topology of FIG. 2, according to an embodiment of the present invention;

FIG. 14 shows example programmed logic states for the plurality of logic cells of FIG. 13;

FIG. 15 shows a programmable AND gate comprising a plurality of logic cells with each logic cell having the circuit topology of FIG. 6, according to an embodiment of the present invention; and

FIG. 16 shows example programmed logic states for the plurality of logic cells of FIG. 15.

The figures referred to herein are drawn for clarity of illustration and are not necessarily drawn to scale. Elements having the same reference number in FIGS. 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, and 16 refer to elements having similar structure and function.

DETAILED DESCRIPTION

Referring to FIG. 2, a first embodiment of a zero-power programmable logic cell 200 is implemented in CMOS (complementary metal oxide semiconductor) technology. The programmable logic cell 200 includes a first pair of stacked PMOSFETs (P-channel metal oxide semiconductor field effect transistors) 202 coupled between a first rail voltage V_{CC1} and an output node 204. In addition, a second pair of stacked PMOSFETs (P-channel metal oxide semiconductor field effect transistors) 206 is coupled between a second rail voltage V_{CC2} and the output node 204.

Furthermore, a first pair of stacked NMOSFETs (N-channel metal oxide semiconductor field effect transistors) 208 is coupled between a third rail voltage V_{SS1} and the output node 204, and a second pair of stacked NMOSFETs (N-channel metal oxide semiconductor field effect transistors) 210 is coupled between a fourth rail voltage V_{SS2} and the output node 204. In one embodiment of the present invention, the first and second rail voltages V_{CC1} and V_{CC2} are at the voltage level of 1.8 Volts, and the third and fourth rail voltages V_{SS1} and V_{SS2} are at the ground voltage level of 0 Volts.

Further referring to FIG. 2, the gate of a first PMOSFET 212 of the first pair of PMOSFETs 202 is coupled to an output M_{OUT1} of a first memory cell 214. In addition, a second PMOSFET 216 of the first pair of PMOSFETs 202 has the gate coupled to a first input signal, I_1 , at a first input node 218 and has the drain coupled to the output node 204. The first PMOSFET 212 and the second PMOSFET 216 are stacked with the drain of the first PMOSFET 212 being coupled to the source of the second PMOSFET 216.

Furthermore, a first NMOSFET 220 of the first pair of NMOSFETs 208 has the gate coupled to the first input signal, I_1 , on the first input node 218 and has the drain coupled to the output node 204. In addition, the gate of a second NMOSFET 222 of the first pair of NMOSFETs 208 is coupled to a second input signal, I_2 , at a second input node 224. The first NMOSFET 220 and the second NMOSFET 222 are stacked with the source of the first NMOSFET 220 being coupled to the drain of the second NMOSFET 222.

Additionally, the gate of a third PMOSFET 226 of the second pair of PMOSFETs 206 is coupled to an output M_{OUT2} of a second memory cell 228. Furthermore, a fourth PMOSFET 230 of the second pair of PMOSFETs 206 has the gate coupled to the second input signal, I_2 , at the second input node 224 and has the drain coupled to the output node 204. The third PMOSFET 226 and the fourth PMOSFET

230 are stacked with the drain of the third PMOSFET 226 being coupled to the source of the fourth PMOSFET 230.

Also, a third NMOSFET 232 of the second pair of NMOSFETs 210 has the gate coupled to the output of the first memory cell 214 and has the drain coupled to the output node 204. In addition, the gate of a fourth NMOSFET 234 of the second pair of NMOSFETs 210 is coupled to the output of the second memory cell 228. The third NMOSFET 232 and the fourth NMOSFET 234 are stacked with the source of the third NMOSFET 232 being coupled to the drain of the fourth NMOSFET 234. The drain of the second NMOSFET 222 is coupled to the drain of the fourth NMOSFET 234.

The first and second input signals, I_1 and I_2 , are determined by an input signal selection circuit 236 of FIG. 3. A logic cell input signal, I , is coupled to a logic cell input signal node 237 of the input signal selection circuit 236. In addition, a first logic state, V_1 , is coupled to a first logic state input node 238, and a second logic state, V_2 , is coupled to a second logic state input node 239. A first switch 240 is switched between coupling the logic cell input signal, I , at the logic cell input signal node 237 or the first logic state, V_1 , at the first logic state input node 238 to the input of a first inverter 241. A second switch 242 is switched between coupling the output of the first inverter 241 or the second logic state, V_2 , at the second logic state input node 239 to the second input node 224 for providing the second input signal, I_2 , of the logic cell 200. The output of the first inverter 241 is input to a second inverter 243, and the output of the second inverter 243 is coupled to the first input node 218 for providing the first input signal, I_1 , of the logic cell 200.

During a functional mode of the logic cell 200, the first switch 240 is at the switched position for coupling the logic cell input signal, I , to the input of the first inverter 241, and the second switch 242 is at the switched position for coupling the output of the first inverter 241 to the second input node 224 of the logic cell 200, as illustrated in FIG. 3. Thus, in the functional mode of FIG. 3, the logic cell input signal, I , is formed as the first input signal, I_1 , at the first input node 218 of the logic cell 200, and the complement of the logic cell input signal designated as I^* , is formed as the second input signal, I_2 , at the second input node 224 of the logic cell 200.

Referring to FIG. 4, in a verify mode of the logic cell 200, the first switch 240 is at the switched position for coupling the first logic state, V_1 , to the input of the first inverter 241, and the second switch 242 is at the switched position for coupling the second logic state, V_2 , to the second input node 224 of the logic cell 200. In the verify mode of FIG. 4, the first logic state, V_1 , is formed as the first input signal, I_1 , at the first input node 218 of the logic cell 200, and the second logic state, V_2 , is formed as the second input signal, I_2 , at the second input node 224 of the logic cell 200.

During the verify mode, the first logic state, V_1 , is applied at the first logic state input node 238 that is separate from the second logic state input node 239 having the second logic state, V_2 , applied thereon. Thus, the first logic state, V_1 , formed as the first input signal, I_1 , at the first input node 218 of the logic cell 200 is independent from the second logic state, V_2 , formed as the second input signal, I_2 , at the second input node 224 of the logic cell 200, during the verify mode. In contrast, in the functional mode, the first input signal, I_1 , at the first input node 218 and the second input signal, I_2 , at the second input node 224 are complements of each other.

FIG. 5 shows a truth table of the output signal formed at the output node 204 of the logic cell 200 of FIG. 2 for

various logic states of the first input signal, I_1 , and the second input signal, I_2 , and for various logic states of the first output, M_{OUT1} , of the first memory cell **214** and of the second output, M_{OUT2} , of the second memory cell **228**. “1” represents a logical high state, and “0” represents a logical low state. A first block **244** of the rows of the truth table of FIG. **5** is for the functional mode of the logic cell **200** when the first input signal, I_1 , and the second input signal, I_2 , are complements of each other. Referring to FIGS. **2** and **3**, during such a functional mode, the first input signal, I_1 , is the logic cell input signal I , and the second input signal, I_2 , is the complement of the logic cell input signal, I^* .

During the functional mode of the logic cell **200** of FIG. **2**, the output signal at the output node **204** is determined by the logic states programmed within the first and second memory cells **214** and **228**. The output of each of the first and second memory cells **214** and **228** is programmed to be one of a logical high state or a logical low state. Then, depending on such outputs M_{OUT1} and M_{OUT2} of the first and second memory cells **214** and **228**, the output signal at the output node **204** of the logic cell **200** during the functional mode is determined according to the following truth table:

M_{OUT1}	M_{OUT2}	OUTPUT
0	0	1
0	1	$I_1^* = I^* = I_2$
1	0	$I_2^* = I = I_1$
1	1	0

Thus, in the functional mode, the logic cell **200** is programmed to have one of four outputs, “0”, “1”, “I”, or “I*” by programming the logic state at the respective output of each of the first and second memory cells **214** and **228**. In addition, the example embodiment of the logic cell **200** of FIG. **2** is implemented in CMOS technology with the first and second pairs of stacked PMOSFETs **202** and **206** and with the first and second pairs of stacked NMOSFETs **208** and **210**. Furthermore, the logic cell **200** is a zero-power logic cell because each node of the circuit of the logic cell **200** of FIG. **2** is either charged up to a logical high state or is charged down to a logical low state without any steady-state current dissipation.

In the programmable logic cell **200**, the gate of the first NMOSFET **220** is coupled to the first input signal, I_1 , and the gate of the second NMOSFET **222** is coupled to the second input signal I_2 . The gate of the third NMOSFET **232** is coupled to the output of the first memory cell **214**, and the gate of the fourth NMOSFET **234** is coupled to the output of the second memory cell **228**. Because the third and fourth NMOSFETs **232** and **234** are not in the path of the input signals, I_1 and I_2 , the third and fourth NMOSFETs **232** and **234** may be sized to be smaller (i.e. with a smaller width) than the first and second NMOSFETs **220** and **222** that are in the path of the input signals, I_1 and I_2 . With such a smaller size, the third and fourth NMOSFETs **232** and **234** advantageously contribute less parasitic capacitance at the output node **204**.

Referring to FIG. **6**, a second embodiment of a zero-power programmable logic cell **246** is implemented in CMOS (complementary metal oxide semiconductor) technology. Similar to the first embodiment of the logic cell **200** of FIG. **2**, the second embodiment of the logic cell **246** of FIG. **6** includes the first pair of stacked PMOSFETs **202**, the second pair of stacked PMOSFETs **206**, the first pair of

stacked NMOSFETs **208**, and the second pair of stacked NMOSFETs **210**.

However, in contrast to the first embodiment of the logic cell **200** of FIG. **2**, for the second embodiment of the logic cell **246** of FIG. **6**, the gate of the first PMOSFET **212** and the gate of the third NMOSFET **232** are coupled to the second input signal, I_2 , (instead of to the first output M_{OUT1} of the first memory cell **214**). In addition, the gate of the second NMOSFET **222** and the gate of the fourth PMOSFET **230** are coupled to the first output M_{OUT1} of the first memory cell **214** (instead of to the second input signal, I_2). Furthermore, the drain of the first PMOSFET **212** is coupled to the drain of the third PMOSFET **226** (instead of the drain of the second NMOSFET **222** being coupled to the drain of the fourth NMOSFET **234**).

FIG. **7** shows a truth table of the output signal formed at the output node **204** of the logic cell **246** of FIG. **6** for various logic states of the first input signal, I_1 , and the second input signal, I_2 , and for various logic states of the first output, M_{OUT1} , of the first memory cell **214** and of the second output, M_{OUT2} , of the second memory cell **228**. “1” represents a logical high state, and “0” represents a logical low state. A first block **248** of the rows of the truth table of FIG. **7** is for the functional mode of the logic cell **246** when the first input signal, I_1 , and the second input signal, I_2 , are complements of each other. Referring to FIGS. **3** and **6**, during such a functional mode, the first input signal, I_1 , is the logic cell input signal I , and the second input signal, I_2 , is the complement of the logic cell input signal, I^* .

During the functional mode of the logic cell **246** of FIG. **6**, the output signal at the output node **204** is determined by the logic states programmed within the first and second memory cells **214** and **228**. The output of each of the first and second memory cells **214** and **228** is programmed to be one of a logical high state or a logical low state. Then, depending on such outputs M_{OUT1} and M_{OUT2} of the first and second memory cells **214** and **228**, the output signal at the output node **204** for the logic cell **246** during the functional mode is determined according to the following truth table:

M_{OUT1}	M_{OUT2}	OUTPUT
0	0	1
0	1	$I_2^* = I_1 = I$
1	0	$I_1^* = I_2 = I^*$
1	1	0

Thus, in the functional mode, the logic cell **246** of FIG. **6** is also programmed to have one of four outputs, “0”, “1”, “I”, or “I*” by programming the logic state at the respective output of each of the first and second memory cells **214** and **228**, similar to the logic cell **200** of FIG. **2**. In addition, the example embodiment of the logic cell **246** of FIG. **6** is also implemented in CMOS technology with the first and second pairs of stacked PMOSFETs **202** and **206** and with the first and second pairs of stacked NMOSFETs **208** and **210**. Furthermore, the logic cell **246** of FIG. **6** is also a zero-power logic cell because each node of the circuit of the logic cell **246** of FIG. **6** is either charged up to a logical high state or is charged down to a logical low state without any steady-state current dissipation.

Referring to FIG. **8**, a zero-power memory cell **250** that is electrically erasable and programmable is used for each of the first and second memory cells **214** and **228** of FIGS. **2**

or 6, according to one embodiment of the present invention. However, the logic cell 200 of FIG. 2 or the logic cell 246 of FIG. 6 may be used with other types of programmable memory cells aside from the example implementation of FIG. 8, as would be apparent to one of ordinary skill in the art of programmable logic devices from the description herein.

The zero-power memory cell 250 of FIG. 8 includes a sense PMOSFET 252 and a sense NMOSFET 254. The drain of the sense PMOSFET 252 and the drain of the sense NMOSFET 254 are coupled together to form an output node 256 of the memory cell 250. The gate of the sense PMOSFET 252 and the gate of the sense NMOSFET 254 are coupled together to form a floating gate 258 of the memory cell 250. The source of the sense PMOSFET 252 is coupled to a first variable voltage generator 260 that provides a first variable voltage V_D , and the source of the sense NMOSFET 254 is coupled to a second variable voltage generator 262 that provides a second variable voltage V_S .

A control gate voltage source 264 is coupled to a control gate node 266, and a coupling capacitor 268 couples the control gate node 266 to the floating gate 258 of the memory cell 250. Furthermore, a tunneling capacitor 270 is coupled between the floating gate 258 and a drain of a write NMOSFET 272. The tunneling capacitor 270 is comprised of a tunneling oxide 274 disposed between overlapping polysilicon layers 276 and 278, according to an embodiment of the present invention. With sufficient voltage across the tunneling capacitor 270, charge carriers tunnel through the tunneling oxide 274, as known to one of ordinary skill in the art of electronics. In addition, the gate of the write NMOSFET 272 is coupled to a WL (write line) 280 having a WL (write line) voltage source 282 coupled thereon, and the source of the write NMOSFET 272 is coupled to a WBL (write bit line) 284 having a WBL (write bit line) voltage source 286 coupled thereon.

The electrically erasable and programmable zero-power memory cell 250 of FIG. 8 operates according to the voltages of the table of FIG. 9 in one embodiment of the present invention. During an erase operation, a positive voltage of about $V_{PP+}=12$ Volts is applied on the CG node from the CG voltage source 264, a positive voltage of about $V_{dd}=1.8$ Volts is applied on the WL (write line) 280, and a ground voltage of 0 Volts is applied on the WBL (write bit line) 284. With such an erase bias, the write transistor 272 turns on. Because of the high positive voltage of $V_{PP+}=12$ Volts on the CG node 266, electrons tunnel through the tunneling capacitor 270 to the floating gate 258 such that a negative voltage is stored on the floating gate 258. With such a negative voltage on the floating gate 258, the sense NMOSFET 254 remains turned off, and the sense PMOSFET 252 turns on such that a logical high state (i.e., a voltage level of $V_{dd}=1.8$ Volts) forms as the output signal M_{OUT} on the output node 256 of the memory cell 250.

In addition, according to an embodiment of the present invention, a positive voltage of $V_{dd}=1.8$ Volts is generated by each of both the first and second variable voltage sources 260 and 262 (i.e., as V_D and V_S) and are applied on the respective source of each of the sense PMOSFET 252 and the sense NMOSFET 254 during the erase operation. Such a positive voltage for the V_D and V_S applied on the respective source of each of the sense PMOSFET 252 and the sense NMOSFET 254 is advantageous for further attracting negative charge to the floating gate 258 during the erase operation. Thus, the positive voltage for the V_D and V_S ensures maximized capacitive coupling for the coupling capacitor 268 in forming a negative voltage on the floating gate 258 during the erase operation.

During a program operation, a ground voltage of 0 Volts is applied on the CG node from the CG voltage source 264, a positive voltage of about $V_{PP+}=12$ Volts is applied on the WL (write line) 280, and a positive voltage of about $V_{PP}=11$ Volts is applied on the WBL (write bit line) 284. With such a program bias, the write transistor 272 turns on. Because of the high positive voltage of $V_{PP}=11$ Volts on the WBL (write bit line) 284, electrons tunnel through the tunneling capacitor 270 away from the floating gate 258 and positive charge carriers tunnel through the tunnel capacitor 270 to the floating gate 258 such that a positive voltage is stored on the floating gate 258. With such a positive voltage on the floating gate 258, the sense PMOSFET 252 remains turned off and the sense NMOSFET 254 turns on such that a logical low state (i.e., a voltage level of 0 Volts) forms as the output signal M_{OUT} on the output node 256 of the memory cell 250.

In addition, according to an embodiment of the present invention, a ground voltage of 0 Volts is generated by each of both the first and second variable voltage sources 260 and 262 (i.e., as V_D and V_S) and are applied on the respective source of each of the sense PMOSFET 252 and the sense NMOSFET 254 during the program operation. Such a ground voltage for the V_D and V_S applied on the respective source of each of the sense PMOSFET 252 and the sense NMOSFET 254 is advantageous for further repulsing negative charge from the floating gate 258 and attracting positive charge carriers to the floating gate 258 during the program operation. Thus, the ground voltage for the V_D and V_S ensures maximized capacitive coupling for the coupling capacitor 268 in forming a positive voltage on the floating gate 258 during the program operation.

In a further embodiment of the present invention, the magnitude of the respective threshold voltage for each of the sense PMOSFET 252 and the sense NMOSFET 254 is higher than a magnitude of a threshold voltage of standard process P-channel and N-channel transistors. For example, for a CMOS technology using a rail-to-rail voltage ($V_{CC}-V_{SS}$) of about 1.8 Volts, the magnitude of the threshold voltage for the P-channel and N-channel transistors in the standard CMOS fabrication process is about 0.5 Volts (i.e., about $\frac{1}{4}$ of the rail-to-rail voltage of 1.8 Volts), as known to one of ordinary skill in the art of integrated circuit fabrication. However, according to one embodiment of the present invention, the magnitude of the threshold voltage for each of the sense PMOSFET 252 and the sense NMOSFET 254 is about $\frac{1}{2}$ of a minimum value of the possible range of the rail-to-rail voltage.

The rail-to-rail voltage ($V_{CC}-V_{SS}$) for a CMOS process has a range of possible values because of variations in process and environmental parameters, as known to one of ordinary skill in the art of integrated circuit fabrication. For example, the range of possible values of the rail-to-rail voltage ($V_{CC}-V_{SS}$) may be 1.8 Volts \pm 0.2 Volts. In that case, the minimum value of the possible range of the rail-to-rail voltage is 1.6 Volts. For the memory cell 250 fabricated in the CMOS process having such a range of possible values of the rail-to-rail voltage, the magnitude of the respective threshold voltage for each of the sense PMOSFET 252 and the sense NMOSFET 254 is about $\frac{1}{2}$ of the minimum value of the possible range of the rail-to-rail voltage (i.e., 0.8 Volts= $\frac{1}{2}$ of 1.6 Volts), according to one embodiment of the present invention. Generally, the sum of the magnitudes of each of the respective threshold voltage for the sense PMOSFET 252 and the sense NMOSFET 254 is equal to or greater than the minimum value of the possible range of the rail-to-rail voltage applied across the sources of the sense PMOSFET 252 and the sense NMOSFET 254 during a read

operation of the memory cell, according to an embodiment of the present invention.

Such a higher magnitude of the threshold voltage for each of the sense PMOSFET **252** and the sense NMOSFET **254** is achieved by adjusting the respective gate oxide thickness and the concentration of the respective channel doping for each of the sense PMOSFET **252** and the sense NMOSFET **254**. Referring to FIG. **10**, the sense NMOSFET **254** is fabricated within a P-type substrate **302**, and the sense PMOSFET **252** is fabricated within an N-well **304** formed within the P-type substrate **302**. A shallow trench isolation structure **306** electrically isolates the sense PMOSFET **252** and the sense NMOSFET **254**. Processes for fabricating such integrated circuit device structures are known to one of ordinary skill in the art of integrated circuit fabrication.

Referring to FIG. **10**, before formation of the gate oxide for the sense PMOSFET **252** and the sense NMOSFET **254**, a first channel doping implantation is performed for implanting a first channel dopant into the portion of the P-type substrate **302** for forming the sense NMOSFET **254**. The first channel dopant that is implanted for an N-channel region of the sense NMOSFET **254** is comprised of a P-type dopant such as boron for example for adjusting the threshold voltage of the sense NMOSFET **254**. A higher concentration of such a P-type channel dopant increases the threshold voltage of an NMOSFET. A first masking structure **308** which is comprised of photoresist material according to one embodiment of the present invention covers the N-well **304** such that the first channel dopant is not implanted into the N-well **304**.

Referring to FIG. **11**, a second channel doping implantation is performed for implanting a second channel dopant into the N-well for forming the sense PMOSFET **252**. The second channel dopant that is implanted for a P-channel region of the sense PMOSFET **252** is comprised of an N-type dopant such as phosphorous and/or arsenic for example for adjusting the threshold voltage of the sense PMOSFET **252**. A higher concentration of such an N-type channel dopant increases the threshold voltage of a PMOSFET. A second masking structure **310** which is comprised of photoresist material according to one embodiment of the present invention covers the portion of the P-type substrate **302** for forming the NMOSFET therein such that the second channel dopant is not implanted into that portion of the P-type substrate **302**. Implantation processes for the first and second channel doping implantation of FIGS. **10** and **11** are known to one of ordinary skill in the art of integrated circuit fabrication.

Referring to FIG. **12**, after the first and second channel doping implantations, an N-channel gate oxide **312** and an N-channel gate structure **314** are formed on the portion of the P-type substrate **302** for forming the sense NMOSFET **254**, and a P-channel gate oxide **316** and a P-channel gate structure **318** are formed on the N-well **304**. In addition, an N-channel drain **320** and an N-channel source **322** are formed for the sense NMOSFET **254** with an N-channel region **324** being formed beneath the N-channel gate oxide **312** between the N-channel drain **320** and source **322**. Similarly, a P-channel drain **330** and a P-channel source **332** are formed for the sense PMOSFET **252** with a P-channel region **334** being formed beneath the P-channel gate oxide **316** between the P-channel drain **330** and source **332**. Processes for formation of such structures for an NMOSFET and for a PMOSFET are known to one of ordinary skill in the art of integrated circuit fabrication.

The N-channel gate oxide **312** has a first thickness **336**, and the P-channel gate oxide **316** has a second thickness

338. A higher gate oxide thickness of a MOSFET increases the magnitude of the threshold voltage of the MOSFET. The gate oxide thickness for a low voltage MOSFET is approximately 40 Å, and the gate oxide thickness for a high voltage MOSFET is approximately 90 Å. As known to one of ordinary skill in the art of integrated circuit fabrication, the high voltage MOSFET has a higher gate oxide thickness than the low voltage MOSFET to prevent gate oxide degradation in the high voltage MOSFET from higher bias voltages applied on the high voltage MOSFET.

In the prior art, for a rail voltage V_{CC} of about 1.8 Volts, a high voltage MOSFET or a low voltage MOSFET has a magnitude of a threshold voltage of about 0.5 Volts. To achieve such a constant magnitude of the threshold voltage, the concentration of the channel dopant for a high voltage MOSFET is lower than the concentration of the channel dopant for a low voltage MOSFET.

For example, for a high voltage NMOSFET having a higher gate oxide thickness of about 90 Å with the channel dopant being comprised of boron, the concentration of the channel dopant is about $3.5 \times 10^{12}/\text{cm}^2$ to attain a magnitude of the threshold voltage of the high voltage NMOSFET to be about 0.5 Volts. On the other hand, for a low voltage NMOSFET having a lower gate oxide thickness of about 40 Å with the channel dopant being comprised of boron, the concentration of the channel dopant is about $1.1 \times 10^{13}/\text{cm}^2$ to attain a magnitude of the threshold voltage of the low voltage NMOSFET to also be about 0.5 Volts.

Similarly, for a high voltage PMOSFET having a higher gate oxide thickness of about 90 Å with the channel dopant being comprised of phosphorous and/or arsenic, the concentration of the channel dopant is about $2.7 \times 10^{12}/\text{cm}^2$ to attain a magnitude of the threshold voltage of the high voltage PMOSFET to be about 0.5 Volts. On the other hand, for a low voltage PMOSFET having a lower gate oxide thickness of about 40 Å with the channel dopant being comprised of phosphorous and/or arsenic, the concentration of the channel dopant is about $1.1 \times 10^{13}/\text{cm}^2$ to attain a magnitude of the threshold voltage of the low voltage PMOSFET to also be about 0.5 Volts.

In an embodiment of the present invention, the sense PMOSFET **252** and the sense NMOSFET **254** have a higher magnitude of threshold voltage that is about 0.8 Volts by having the higher gate oxide thickness of a high voltage MOSFET in conjunction with a higher concentration of channel dopant for a low voltage MOSFET. Thus, referring to FIG. **7**, the first thickness **336** of the N-channel gate oxide **312** for the sense NMOSFET **254** is about 90 Å. In addition, referring to FIG. **5**, the concentration of the P-type channel dopant such as boron for example for the sense NMOSFET **254** is about $1.1 \times 10^{13}/\text{cm}^2$ to attain a magnitude of the threshold voltage of the sense NMOSFET **254** that is about 0.8 Volts according to one embodiment of the present invention.

Similarly, referring to FIG. **12**, the second thickness **338** of the P-channel gate oxide **316** for the sense PMOSFET **252** is about 90 Å. Furthermore, referring to FIG. **11**, the concentration of the N-type channel dopant such as phosphorous and/or arsenic for example for the sense PMOSFET **252** is about $1.1 \times 10^{13}/\text{cm}^2$ to attain a magnitude of the threshold voltage of the sense PMOSFET **252** that is about 0.8 Volts according to one embodiment of the present invention.

Referring to FIG. **8**, a higher magnitude of the respective threshold voltage for each of the sense PMOSFET **252** and the sense NMOSFET **254** is advantageous for ensuring that

the sense PMOSFET **252** and the sense NMOSFET **254** are turned off at proper times to minimize undesired current dissipation in the memory cell **250**. In addition, a higher magnitude of the respective threshold voltage for each of the sense PMOSFET **252** and the sense NMOSFET **254** is advantageous for operation of the memory cell **250** with a lower magnitude of the voltage stored on the floating gate **258** of the memory cell **250**.

For example, referring to FIG. **8**, assume that -0.5 Volts is stored on the floating gate **258** of the memory cell **250** after the erase operation, and that $+0.5$ Volts is stored on the floating gate **258** of the memory cell **250** after the program operation. During the read operation (i.e., the normal operation) after an erase operation, a voltage of 0.9 Volts is applied on the WBL (write bit line) **284**. In that case, a voltage of $0.4 (=0.9-0.5)$ Volts forms at the floating gate **258** of the memory cell **250** such that the source to gate voltage V_{SG} of the sense PMOSFET **252** is about 1.4 Volts and such that the gate to source voltage V_{GS} of the sense NMOSFET **254** is about 0.4 Volts.

During the read operation after an erase operation, it is desired that the sense PMOSFET **252** turn on and that the sense NMOSFET **254** remain turned off. If the magnitude of the respective threshold voltage of each of the sense PMOSFET **252** and the sense NMOSFET **254** is only about 0.5 Volts, then the sense PMOSFET **252** is turned on with the source to gate voltage V_{SG} of the sense PMOSFET **252** being about 1.4 Volts. However, with the gate to source voltage V_{GS} of the sense NMOSFET **254** being about 0.4 Volts, the NMOSFET **254** may also turn on in weak inversion when the magnitude of the threshold voltage of sense NMOSFET **254** is as low as 0.5 Volts. When the PMOSFET **252** is turned on and when the NMOSFET **254** is also turned on in weak inversion, current is undesirably dissipated through the memory cell **250** such that the memory cell **250** is disadvantageously no longer a zero-power memory cell.

For ensuring that the sense NMOSFET **254** remains turned off during such a read operation, a more negative voltage may be stored on the floating gate **258** during the prior erase operation. However, such a solution disadvantageously requires higher voltages and longer time periods of the erasing operation. Rather, according to one embodiment of the present invention, a higher threshold voltage of the sense NMOSFET **254** ensures that the sense NMOSFET **254** remains turned off during such a read operation. When the threshold voltage of the sense NMOSFET **254** is about 0.8 Volts, the sense NMOSFET **254** remains turned off when the gate to source voltage V_{GS} of the sense NMOSFET **254** is about 0.4 Volts during such a read operation.

In a similar manner, a higher magnitude of the threshold voltage of the sense PMOSFET **252** further ensures that the sense PMOSFET **252** remains turned off when the sense NMOSFET **254** turns on during the read operation after a program operation. Thus, a higher magnitude of the respective threshold voltage for each of the sense PMOSFET **252** and the sense NMOSFET **254** further ensures that one of the sense PMOSFET **252** and the sense NMOSFET **254** remains turned off during a read operation to minimize undesired current dissipation through the memory cell **250** such that the memory cell **250** is a zero-power memory cell. In addition, a higher magnitude of the respective threshold voltage for each of the sense PMOSFET **252** and the sense NMOSFET **254** further ensures that one of the sense PMOSFET **252** and the sense NMOSFET **254** remains turned off during a read operation with a lower magnitude of voltage stored on the floating gate **258** during the erase and program operations such that lower voltages and time periods advantageously may be used during the erase and program operations.

Referring to FIGS. **2**, **6**, and **8**, the memory cell **250** of FIG. **8** that is a zero-power memory cell is used as each of the first and second memory cells **214** and **228** in the zero-power logic cell **200** of FIG. **2** or the zero-power logic cell **246** of FIG. **6**. Either one of the logic cell **200** of FIG. **2** with two of the memory cell **250** of FIG. **8** or the logic cell **246** of FIG. **6** with two of the memory cell **250** of FIG. **8** is advantageously used to implement a zero-power logic cell in a programmable logic device.

For example, referring to FIG. **13**, an eight-input programmable OR gate **400** includes a first zero-power programmable logic cell **402**, a second zero-power programmable logic cell **404**, a third zero-power programmable logic cell **406**, a fourth zero-power programmable logic cell **408**, a fifth zero-power programmable logic cell **410**, a sixth zero-power programmable logic cell **412**, a seventh zero-power programmable logic cell **414**, and an eighth zero-power programmable logic cell **416**. Each of these logic cells **402**, **404**, **406**, **408**, **410**, **412**, **414**, and **416** has the implementation of the programmable zero-power logic cell **200** of FIG. **2** or the programmable zero-power logic cell **246** of FIG. **6**, each with a respective input signal selection circuit (implemented as the input signal selection circuit **236** of FIG. **3**) and with the first and second memory cells **214** and **228** being implemented as the memory cell **250** of FIG. **8**.

Further referring to FIGS. **2**, **3**, **6**, and **13**, the first logic cell **402** inputs a first logic cell input signal A as the logic cell input signal, I, of the respective input signal selection circuit corresponding to the first logic cell **402**. Thus, the first logic cell **402** provides an output signal OUT_A as one of the first logic cell input signal A, the complement of the first logic cell input signal A*, a logical high state "1", or a logical low state "0" depending on whether the logical low or high state is programmed or erased within each of the respective two memory cells of the first logic cell **402**, during the functional mode of the programmable OR gate **400**.

Similarly, the second logic cell **404** inputs a second logic cell input signal B as the logic cell input signal, I, of the respective input signal selection circuit corresponding to the second logic cell **404**. Thus, the second logic cell **404** provides an output signal OUT_B as one of the second logic cell input signal B, the complement of the second logic cell input signal B*, a logical high state "1", or a logical low state "0" depending on whether the logical low or high state is programmed or erased within each of the respective two memory cells of the second logic cell **404**, during the functional mode of the programmable OR gate **400**.

In addition, the third logic cell **406** inputs a third logic cell input signal C as the logic cell input signal, I, of the respective input signal selection circuit corresponding to the third logic cell **406**. Thus, the third logic cell **406** provides an output signal OUT_C as one of the third logic cell input signal C, the complement of the third logic cell input signal C*, a logical high state "1", or a logical low state "0" depending on whether the logical low or high state is programmed or erased within each of the respective two memory cells of the third logic cell **406**, during the functional mode of the programmable OR gate **400**.

Similarly, the fourth logic cell **408** inputs a fourth logic cell input signal D as the logic cell input signal, I, of the respective input signal selection circuit corresponding to the fourth logic cell **408**. Thus, the fourth logic cell **408** provides an output signal OUT_D as one of the fourth logic cell input signal D, the complement of the fourth logic cell input signal D*, a logical high state "1", or a logical low state "0"

depending on whether the logical low or high state is programmed or erased within each of the respective two memory cells of the fourth logic cell **408**, during the functional mode of the programmable OR gate **400**.

Furthermore, the fifth logic cell **410** inputs a fifth input signal E as the logic cell input signal, I, of the respective input signal selection circuit corresponding to the fifth logic cell **410**. Thus, the fifth logic cell **410** provides an output signal OUT_E as one of the fifth logic cell input signal E, the complement of the fifth logic cell input signal E^* , a logical high state "1", or a logical low state "0" depending on whether the logical low or high state is programmed or erased within each of the respective two memory cells of the fifth logic cell **410**, during the functional mode of the programmable OR gate **400**.

Similarly, the sixth logic cell **412** inputs a sixth input signal F as the logic cell input signal, I, of the respective input signal selection circuit corresponding to the sixth logic cell **412**. Thus, the sixth logic cell **412** provides an output signal OUT_F as one of the sixth logic cell input signal F, the complement of the sixth logic cell input signal F^* , a logical high state "1", or a logical low state "0" depending on whether the logical low or high state is programmed or erased within each of the respective two memory cells of the sixth logic cell **412**, during the functional mode of the programmable OR gate **400**.

Also, the seventh logic cell **414** inputs a seventh input signal G as the logic cell input signal, I, of the respective input signal selection circuit corresponding to the seventh logic cell **414**. Thus, the seventh logic cell **414** provides an output signal OUT_G as one of the seventh logic cell input signal G, the complement of the seventh logic cell input signal G^* , a logical high state "1", or a logical low state "0" depending on whether the logical low or high state is programmed or erased within each of the respective two memory cells of the seventh logic cell **414**, during the functional mode of the programmable OR gate **400**.

Similarly, the eighth logic cell **416** inputs an eighth input signal H as the logic cell input signal, I, of the respective input signal selection circuit corresponding to the eighth logic cell **416**. Thus, the eighth logic cell **416** provides an output signal OUT_H as one of the eighth logic cell input signal H, the complement of the eighth logic cell input signal H^* , a logical high state "1", or a logical low state "0" depending on whether the logical low or high state is programmed or erased within each of the respective two memory cells of the eighth logic cell **416**, during the functional mode of the programmable OR gate **400**.

The outputs, OUT_A and OUT_B , of the first and second logic cells **402** and **404** are inputs to a first 2-input NOR gate **422**. The outputs, OUT_C and OUT_D , of the third and fourth logic cells **406** and **408** are inputs to a second 2-input NOR gate **424**. The outputs, OUT_E and OUT_F , of the fifth and sixth logic cells **410** and **412** are inputs to a third 2-input NOR gate **426**. The outputs, OUT_G and OUT_H , of the seventh and eighth logic cells **414** and **416** are inputs to a fourth 2-input NOR gate **428**.

The outputs of the first and second NOR gates **422** and **424** are inputs to a first 2-input NAND gate **432**. The outputs of the third and fourth NOR gates **426** and **428** are inputs to a second 2-input NAND gate **434**. The outputs of the first and second NAND gates **432** and **434** are inputs to a fifth 2-input NOR gate **442**. The output of the fifth NOR gate **442** is inverted through an inverter **444** to form the OUTPUT signal at the output node **446**. The OUTPUT signal at the output node **446** of the programmable OR gate **400** of FIG. **13** is expressed as follows:

$$OUTPUT=OUT_A+OUT_B+OUT_C+OUT_D+OUT_E+OUT_F+OUT_G+OUT_H$$

Thus, the outputs of each of the logic cells **402**, **404**, **406**, **408**, **410**, **412**, **414**, and **416** are OR'ed together to form the OUTPUT signal at the output node **446** of the programmable OR gate **400**. Referring to FIGS. **2**, **6**, and **13**, for programming the programmable OR gate **400** of FIG. **13**, the respective two memory cells **214** and **218** of each of the logic cells **402**, **404**, **406**, **408**, **410**, **412**, **414**, and **416** are each programmed or erased to output a logical low state or a logical high state, respectively, for a desired respective output signal at the logic cell during the functional mode of the programmable OR gate **400**.

For example, referring to FIG. **14**, the respective two memory cells of the first logic cell **402** are each erased or programmed such that the output of the first logic cell $OUT_A="0"$ (i.e., a logical low state). The respective two memory cells of the second logic cell **404** are each erased or programmed such that the output of the second logic cell $OUT_B=B^*$ (i.e., the complement of the second input signal B). The respective two memory cells of the third logic cell **406** are each erased or programmed such that the output of the third logic cell $OUT_C=C$ (i.e., the third input signal C). The respective two memory cells of the fourth logic cell **408** are each erased or programmed such that the output of the fourth logic cell $OUT_D=D^*$ (i.e., the complement of the fourth input signal D).

In addition, the respective two memory cells of the fifth logic cell **410** are each erased or programmed such that the output of the fifth logic cell $OUT_E="0"$ (i.e., a logical low state). The respective two memory cells of the sixth logic cell **412** are each erased or programmed such that the output of the sixth logic cell $OUT_F=F$ (i.e., the sixth input signal F). The respective two memory cells of the seventh logic cell **414** are each erased or programmed such that the output of the seventh logic cell $OUT_G=G^*$ (i.e., the complement of the seventh input signal G). The respective two memory cells of the eighth logic cell **416** are each erased or programmed such that the output of the eighth logic cell $OUT_H="0"$ (i.e., a logical low state).

In this example, the OUTPUT signal of the programmable OR gate **400** of FIG. **14** during the functional mode of the programmable OR gate **400** is expressed as follows:

$$OUTPUT=B^*+C+D^*+F+G^*$$

In this manner, the respective two memory cells of each of the logic cells **402**, **404**, **406**, **408**, **410**, **412**, **414**, and **416** may each be erased or programmed to provide an OR functionality of any combination of the eight input signals, A, B, C, D, E, F, G, and H and their complements A^* , B^* , C^* , D^* , E^* , F^* , G^* , and H^* , respectively, with the programmable OR gate **400**, as would be apparent to one of ordinary skill in the art of electronics from the description herein.

Note that if the output of the respective logic cell for a logic cell input signal is set to be a logical low state, "0", then the input signal does not appear in the expression of the OUTPUT signal for the programmable OR gate **400**. If the output of any of the logic cells **402**, **404**, **406**, **408**, **410**, **412**, **414**, and **416** is set to a logical high state, then the OUTPUT signal is automatically a logical high state for the programmable OR gate **400**.

During the verify mode of the programmable OR gate **400** (instead of the functional mode of the programmable OR gate **400**), the output of each of the respective two memory cells of one of the logic cells **402**, **404**, **406**, **408**, **410**, **412**, **414**, and **416** is determined. If the verify mode is to be used

with the programmable OR gate **400**, the logic cell **200** of FIG. **2** (rather than the logic cell **246** of FIG. **6**) is advantageously used for each of the logic cells **402**, **404**, **406**, **408**, **410**, **412**, **414**, and **416** of the programmable OR gate **400**. Referring to the truth table of FIG. **5** for the logic cell **200** of FIG. **2**, within a second block **251** of the truth table of FIG. **5** when the first input signal I_1 and the second input signal I_2 are both a logical high state "1", the output of the logic cell **200** is a logical low state "0", irrespective of the logical states of the output signals M_{OUT1} and M_{OUT2} of the memory cells.

In a preferred embodiment of the present invention, each of the logic cells **402**, **404**, **406**, **408**, **410**, **412**, **414**, and **416** of the programmable OR gate **400** is implemented as the logic cell **200** of FIG. **2** with a respective input signal selection circuit for each logic cell (implemented as the input signal selection circuit **236** of FIG. **4**). In addition, the first and second input signals I_1 and I_2 for each of the logic cells **402**, **404**, **406**, **408**, **410**, **412**, **414**, and **416** are initially set to a logical high state "1" to result in a logical low state "0" at the respective output of each of the logic cells. Referring to the input signal selection circuit **236** of FIG. **4**, the first switch **240** is switched to couple the first logic state input node **238** having the first logic state V_1 to the input of the first inverter **241**, and the second switch **242** is switched to couple the second logic state V_2 at the second logic state input node **239** to the second input node **224** of the logic cell, during the verify mode.

Referring to FIG. **13**, a first logic state V_{A1} and a second logic state V_{A2} are coupled to the first and second logic state input nodes **238** and **239**, respectively, of a respective input signal selection circuit (implemented as the input signal selection circuit **236** of FIG. **4**) corresponding to the first logic cell **402**. Similarly, a first logic state V_{B1} and a second logic state V_{B2} are coupled to the first and second logic state input nodes **238** and **239**, respectively, of a respective input signal selection circuit corresponding to the second logic cell **404**. A first logic state V_{C1} and a second logic state V_{C2} are coupled to the first and second logic state input nodes **238** and **239**, respectively, of a respective input signal selection circuit corresponding to the third logic cell **406**. A first logic state V_{D1} and a second logic state V_{D2} are coupled to the first and second logic state input nodes **238** and **239**, respectively, of a respective input signal selection circuit corresponding to the fourth logic cell **408**.

In like manner, a first logic state V_{E1} and a second logic state V_{E2} are coupled to the first and second logic state input nodes **238** and **239**, respectively, of a respective input signal selection circuit corresponding to the fifth logic cell **410**. A first logic state V_{F1} and a second logic state V_{F2} are coupled to the first and second logic state input nodes **238** and **239**, respectively, of a respective input signal selection circuit corresponding to the sixth logic cell **412**. A first logic state V_{G1} and a second logic state V_{G2} are coupled to the first and second logic state input nodes **238** and **239**, respectively, of a respective input signal selection circuit corresponding to the seventh logic cell **414**. A first logic state V_{H1} and a second logic state V_{H2} are coupled to the first and second logic state input nodes **238** and **239**, respectively, of a respective input signal selection circuit corresponding to the eighth logic cell **416**.

During the verify mode, the respective first and second logic states of each of the logic cells **402**, **404**, **406**, **408**, **410**, **412**, **414**, and **416** (i.e., V_{A1} , V_{A2} , V_{B1} , V_{B2} , V_{C1} , V_{C2} , V_{D1} , V_{D2} , V_{E1} , V_{E2} , V_{F1} , V_{F2} , V_{G1} , V_{G2} , V_{H1} , and V_{H2}) are initially set to a logical high state "1" such that the respective output (i.e., OUT_A , OUT_B , OUT_C , OUT_D , OUT_E , OUT_F , OUT_G , and OUT_H) of each of the logic cells is a logical low state "0".

In this manner, the output signal at the output node **446** of the programmable OR gate **400** is initially a logical low state "0" during the verify mode. Then, for verifying the output of each of the two memory cells **214** and **228** of any one of the logic cells **402**, **404**, **406**, **408**, **410**, **412**, **414**, and **416**, the respective first and second logic states V_1 and V_2 are altered for that logic cell. Referring to FIGS. **2**, **4**, and **5**, for verifying the first output M_{OUT1} of the first memory cell **214**, the first logic state $V_1=I_1$ is set to a logical low state while the second logic state $V_2=I_2$ remains set to the logical high state. Referring to FIG. **5**, in that case, the output signal of a logic cell is a logical high state if the first output M_{OUT1} of the first memory cell **214** is a logical low state, and is a logical low state if the first output M_{OUT1} of the first memory cell **214** is a logical high state.

Alternatively, referring to FIGS. **2**, **4**, and **5**, for verifying the second output M_{OUT2} of the second memory cell **228**, the second logic state $V_2=I_2$ is set to a logical low state while the first logic state $V_1=I_1$ remains set to the logical high state. Referring to FIG. **5**, in that case, the output signal of a logic cell is a logical high state if the second output M_{OUT2} of the second memory cell **228** is a logical low state, and is a logical low state if the second output M_{OUT2} of the second memory cell **228** is a logical high state.

Referring to the programmable OR gate **400** of FIG. **13**, for verifying the first and second outputs M_{OUT1} and M_{OUT2} of any one logic cell, the respective first and second logic states V_1 and V_2 of that logic cell are varied while the respective first and second logic states V_1 and V_2 of the other logic cells of the programmable OR gate **400** are maintained at the logical high state. For example, assume that the first and second outputs M_{OUT1} and M_{OUT2} of the memory cells within the third logic cell **406** are verified. In that case, the respective first and second logic states V_1 and V_2 of each of the first, second, fourth, fifth, sixth, seventh, and eighth logic cells **402**, **404**, **408**, **410**, **412**, **414**, and **416** (i.e., V_{A1} , V_{A2} , V_{B1} , V_{B2} , V_{D1} , V_{D2} , V_{E1} , V_{E2} , V_{F1} , V_{F2} , V_{G1} , V_{G2} , V_{H1} , and V_{H2}) are set to a logical high state "1". Thus, the respective output (i.e., OUT_A , OUT_B , OUT_D , OUT_E , OUT_F , OUT_G , and OUT_H) of each of the logic cell the output signal at the output node **446** of the programmable OR gate **200**.

In addition, for verifying the first output M_{OUT1} of the first memory cell **214** of the third logic cell **406**, the first logic state $V_{C1}=I_1$ is set to a logical low state while the second logic state $V_{C2}=I_2$ remains set to a logical high state. Referring to FIGS. **5** and **13**, in that case, the output signal OUT_C of the third logic cell **406** (and thus the output signal at the output node **446** of the programmable OR gate **400**) is a logical high state if the first output M_{OUT1} of the first memory cell **214** is a logical low state, and is a logical low state if the first output M_{OUT1} of the first memory cell **214** is a logical high state.

Alternatively, for verifying the second output M_{OUT2} of the second memory cell **228** of the third logic cell **406**, the second logic state $V_{C2}=I_2$ is set to a logical low state while the first logic state $V_{C1}=I_1$ remains set to a logical high state. Referring to FIGS. **5** and **13**, in that case, the output signal OUT_C of the third logic cell **406** (and thus the output signal at the output node **446** of the programmable OR gate **400**) is a logical high state if the second output M_{OUT2} of the second memory cell **228** is a logical low state, and is a logical low state if the second output M_{OUT2} of the second first memory cell **228** is a logical high state.

In this manner, the respective logical states of each of the output signals M_{OUT1} and M_{OUT2} of the respective first and second memory cells within the third logic cell **406** is determined during the verify mode. In like manner, the

output signals M_{OUT1} and M_{OUT2} of each respective first and second memory cells within each of the other logic cells **402**, **404**, **408**, **410**, **412**, **414**, and **416** may be individually determined during the verify mode, as would be apparent to one of ordinary skill in the art of electronics from the description herein.

Referring to FIG. 13, when verifying the output signals M_{OUT1} and M_{OUT2} of the memory cells within the third logic cell **406**, the respective output signals (i.e., OUT_A , OUT_B , OUT_D , OUT_E , OUT_F , OUT_G , and OUT_H) of each of the other logic cells **402**, **404**, **408**, **410**, **412**, **414**, and **416** is a logical low state "0" to not affect the output signal at the output node **446** of the programmable OR gate **200**. Referring to the truth table of FIG. 5 for the logic cell **200** of FIG. 2 and to the truth table of FIG. 7 for the logic cell **246** of FIG. 6, the rows of the second block **251** of the truth table of FIG. 5 has the logical low state "0" as the output, irrespective of the logical states of the outputs M_{OUT1} and M_{OUT2} of the memory cells. Therefore, the logic cell **200** of FIG. 2 (rather than the logic cell **246** of FIG. 6) is more amenable for implementing the programmable OR gate **400** with a verify mode.

Similarly, the programmable OR gate **400** of FIG. 13 is a programmable NOR gate with removal of the inverter **444** such that the logic cells **402**, **404**, **406**, **408**, **410**, **412**, **414**, and **416** readily form a programmable NOR gate. As would be apparent to one of ordinary skill in the art of electronics from the description herein, the logic cell **200** of FIG. 2 (rather than the logic cell **246** of FIG. 6) is more amenable for implementing the programmable NOR gate with a verify mode.

On the other hand, FIG. 15 illustrates a programmable AND gate **450** implemented with the programmable zero-power logic cells **402**, **404**, **406**, **408**, **410**, **412**, **414**, and **416**. In contrast to the programmable OR gate **400** of FIG. 13, in the programmable AND gate **450** of FIG. 15, the outputs, OUT_A and OUT_B , of the first and second logic cells **402** and **404** are inputs to a first 2-input NAND gate **452**. The outputs, OUT_C and OUT_D , of the third and fourth logic cells **406** and **408** are inputs to a second 2-input NAND gate **454**. The outputs, OUT_E and OUT_F , of the fifth and sixth logic cells **410** and **412** are inputs to a third 2-input NAND gate **456**. The outputs, OUT_G and OUT_H , of the seventh and eighth logic cells **414** and **416** are inputs to a fourth 2-input NAND gate **458**.

The outputs of the first and second NAND gates **452** and **454** are inputs to a first 2-input NOR gate **462**. The outputs of the third and fourth NAND gates **456** and **458** are inputs to a second 2-input NOR gate **464**. The outputs of the first and second NOR gates **462** and **464** are inputs to a fifth 2-input NAND gate **472**. The output of the fifth NAND gate **472** is inverted through an inverter **474** to form the OUTPUT signal at the output node **476**. The OUTPUT signal at the output node **476** of the programmable AND gate **450** of FIG. 15 is expressed as follows:

$$OUTPUT=OUT_A \cdot OUT_B \cdot OUT_C \cdot OUT_D \cdot OUT_E \cdot OUT_F \cdot OUT_G \cdot OUT_H$$

Thus, the outputs of each of the logic cells **402**, **404**, **406**, **408**, **410**, **412**, **414**, and **416** are AND'ed together to form the OUTPUT signal of the programmable AND gate **450**. Referring to FIGS. 2, 6, and 15, for programming the programmable AND gate **450** of FIG. 15, the respective two memory cells **214** and **218** of each of the logic cells **402**, **404**, **406**, **408**, **410**, **412**, **414**, and **416** are each programmed or erased to output a logical low state or a logical high state, respectively, for a desired respective output signal at the logic cell.

For example, referring to FIG. 16, the respective two memory cells of the first logic cell **402** are each erased or programmed such that the output of the first logic cell $OUT_A=1$ (i.e., a logical high state). The respective two memory cells of the second logic cell **404** are each erased or programmed such that the output of the second logic cell $OUT_B=B^*$ (i.e., the complement of the second input signal B). The respective two memory cells of the third logic cell **406** are each erased or programmed such that the output of the third logic cell $OUT_C=C$ (i.e., the third input signal C). The respective two memory cells of the fourth logic cell **408** are each erased or programmed such that the output of the fourth logic cell $OUT_D=D^*$ (i.e., the complement of the fourth input signal D).

In addition, the respective two memory cells of the fifth logic cell **410** are each erased or programmed such that the output of the fifth logic cell $OUT_E=1$ (i.e., a logical high state). The respective two memory cells of the sixth logic cell **412** are each erased or programmed such that the output of the sixth logic cell $OUT_F=F$ (i.e., the sixth input signal F). The respective two memory cells of the seventh logic cell **414** are each erased or programmed such that the output of the seventh logic cell $OUT_G=G^*$ (i.e., the complement of the seventh input signal G). The respective two memory cells of the eighth logic cell **416** are each erased or programmed such that the output of the eighth logic cell $OUT_H=1$ (i.e., a logical high state).

In this example, the OUTPUT signal of the programmable AND gate **450** of FIG. 16 during the functional mode of the programmable AND gate **450** is expressed as follows:

$$OUTPUT=B^* \cdot C \cdot D^* \cdot F \cdot G^*$$

In this manner, the respective two memory cells of each of the logic cells **402**, **404**, **406**, **408**, **410**, **412**, **414**, and **416** may each be erased or programmed to provide an AND functionality of any combination of the eight input signals A, B, C, D, E, F, G, and H and their complements A^* , B^* , C^* , D^* , E^* , F^* , G^* , and H^* , respectively, with the programmable AND gate **450**, as would be apparent to one of ordinary skill in the art of electronics from the description herein.

Note that if the output of the respective logic cell for an input signal is set to be a logical high state, "1", then the input signal does not appear in the expression of the OUTPUT signal for the programmable AND gate **450**. If the output of any of the logic cells **402**, **404**, **406**, **408**, **410**, **412**, **414**, and **416** is set to a logical low state, then the OUTPUT signal is automatically a logical low state for the programmable AND gate **450**.

In a preferred embodiment of the present invention, each of the logic cells **402**, **404**, **406**, **408**, **410**, **412**, **414**, and **416** of the programmable AND gate **450** is implemented as the logic cell **246** of FIG. 6 with a respective input signal selection circuit (implemented as the input signal selection circuit **236** of FIG. 4). Referring to the truth table of FIG. 7 for the logic cell **246** of FIG. 6, during the verify mode, each of the respective first and second logic states of each of the logic cells **402**, **404**, **406**, **408**, **410**, **412**, **414**, and **416** (i.e., V_{A1} , V_{A2} , V_{B1} , V_{B2} , V_{C1} , V_{C2} , V_{D1} , V_{D2} , V_{E1} , V_{E2} , V_{F1} , V_{F2} , V_{G1} , V_{G2} , V_{H1} , and V_{H2}) is initially set to a logical low state "0" such that the respective output (i.e., OUT_A , OUT_B , OUT_C , OUT_D , OUT_E , OUT_F , OUT_G , and OUT_H) of each of the logic cells is a logical high state "1".

In this manner, the output signal at the output node **476** of the programmable AND gate **450** is initially a logical high state "1" during the verify mode. Then, for verifying the output of each of the two memory cells **214** and **228** of any

one of the logic cells **402**, **404**, **406**, **408**, **410**, **412**, **414**, and **416**, the respective set of the first and second logic states V_1 and V_2 are altered for that logic cell. Referring to FIGS. **4**, **6**, and **7**, for verifying the first output M_{OUT1} of the first memory cell **214**, the first logic state $V_1=I_1$ is set to a logical high state while the second logic state $V_2=I_2$ remains set to the logical low state. Referring to FIG. **7**, in that case, the output signal of a logic cell is a logical high state if the first output M_{OUT1} of the first memory cell **214** is a logical low state, and is a logical low state if the first output M_{OUT1} of the first memory cell **214** is a logical high state.

Alternatively, referring to FIGS. **4**, **6**, and **7**, for verifying the second output M_{OUT2} of the second memory cell **228**, the second logic state $V_2=I_2$ is set to a logical high state while the first logic state $V_1=I_1$ remains set to the logical low state. Referring to FIG. **7**, in that case, the output signal of a logic cell is a logical high state if the second output M_{OUT2} of the second memory cell **228** is a logical low state, and is a logical low state if the second output M_{OUT2} of the second memory cell **228** is a logical high state.

Referring to the programmable AND gate **450** of FIG. **15**, for verifying the first and second outputs M_{OUT1} and M_{OUT2} of any one logic cell, the respective first and second logic states V_1 and V_2 of that logic cell are varied while the respective first and second logic states V_1 and V_2 of the other logic cells of the programmable AND gate **450** are maintained at the logical low state. For example, assume that the first and second outputs M_{OUT1} and M_{OUT2} of the memory cells within the third logic cell **406** are verified. In that case, the respective first and second logic states V_1 and V_2 of each of the first, second, fourth, fifth, sixth, seventh, and eighth logic cells **402**, **404**, **408**, **410**, **412**, **414**, and **416** (i.e., V_{A1} , V_{A2} , V_{B1} , V_{B2} , V_{D1} , V_{D2} , V_{E1} , V_{E2} , V_{F1} , V_{F2} , V_{G1} , V_{G2} , V_{H1} , and V_{H2}) are each set to a logical low state "0". Thus, the respective output (i.e., OUT_A , OUT_B , OUT_D , OUT_E , OUT_F , OUT_G , and OUT_H) of each of the logic cells **402**, **404**, **408**, **410**, **412**, **414**, and **416** is a logical high state "1" and does not affect the output signal at the output node **476** of the programmable AND gate **450**.

In addition, for verifying the first output M_{OUT1} of the first memory cell **214** of the third logic cell **406**, the first logic state $V_{C1}=I_1$ is set to a logical high state while the second logic state $V_{C2}=I_2$ remains set to a logical low state. Referring to FIGS. **7** and **15**, in that case, the output signal OUT_C of the third logic cell **406** (and thus the output signal at the output node **476** of the programmable AND gate **450**) is a logical high state if the first output M_{OUT1} of the first memory cell **214** is a logical low state, and is a logical low state if the first output M_{OUT1} of the first memory cell **214** is a logical high state.

Alternatively, for verifying the second output M_{OUT2} of the second memory cell **228** of the third logic cell **406**, the second logic state $V_{C2}=I_2$ is set to a logical high state while the first logic state $V_{C1}=I_1$ remains set to a logical low state. Referring to FIGS. **7** and **15**, in that case, the output signal OUT_C of the third logic cell **406** (and thus the output signal at the output node **476** of the programmable AND gate **450**) is a logical high state if the second output M_{OUT2} of the second memory cell **228** is a logical low state, and is a logical low state if the second output M_{OUT2} of the second memory cell **228** is a logical high state.

In this manner, the respective logical state of each of the output signals M_{OUT1} and M_{OUT2} of the memory cells within the third logic cell **406** is determined during the verify mode of the programmable AND gate **450**. In like manner, the output signals M_{OUT1} and M_{OUT2} of each respective first and second memory cells within each of the other logic cells

402, **404**, **408**, **410**, **412**, **414**, and **416** may be individually determined during the verify mode of the programmable AND gate **450**, as would be apparent to one of ordinary skill in the art of electronics from the description herein.

Referring to FIG. **15**, when verifying the output signals M_{OUT1} and M_{OUT2} of the memory cells within the third logic cell **406**, the respective output signals (i.e., OUT_A , OUT_B , OUT_D , OUT_E , OUT_F , OUT_G , and OUT_H) of each of the other logic cells **402**, **404**, **408**, **410**, **412**, **414**, and **416** is a logical high state "1" to not affect the output signal at the output node **476** of the programmable AND gate **450**. Referring to the truth table of FIG. **5** for the logic cell **200** of FIG. **2** and to the truth table of FIG. **7** for the logic cell **246** of FIG. **6**, the rows of the second block **253** of the truth table of FIG. **7** has the logical high state "1" as the output irrespective of the logical states of the outputs M_{OUT1} and M_{OUT2} of the memory cells. Therefore, the logic cell **246** of FIG. **6** (rather than the logic cell **200** of FIG. **2**) is more amenable for implementing the programmable AND gate **450** with a verify mode.

Similarly, the programmable AND gate **450** of FIG. **15** is a programmable NAND gate with removal of the inverter **474** such that the logic cells **402**, **404**, **406**, **408**, **410**, **412**, **414**, and **416** readily form a programmable NAND gate. As would be apparent to one of ordinary skill in the art of electronics from the description herein, the logic cell **246** of FIG. **6** (rather than the logic cell **200** of FIG. **2**) is more amenable for implementing the programmable NAND gate with a verify mode.

In this manner, the verification of the outputs M_{OUT1} and M_{OUT2} of the memory cells for each of the logic cells **402**, **404**, **406**, **408**, **410**, **412**, **414**, and **416** is advantageously performed through the logic cells **402**, **404**, **406**, **408**, **410**, **412**, **414**, and **416** such that a separate verification unit is not needed. A separate verification unit may disadvantageously require additional chip space. Rather, with use of the logic cells **402**, **404**, **406**, **408**, **410**, **412**, **414**, and **416** that are implemented as the logic cell **200** of FIG. **2** for programmable OR or NOR gates and that are implemented as the logic cell **246** of FIG. **6** for programmable AND or NAND gates, verification of the outputs M_{OUT1} and M_{OUT2} of the memory cells for each of the logic cells may be performed with just the programmable gates, without any separate additional verification unit, to save chip space.

In addition, programmable logic devices such as the programmable OR gate **400** of FIG. **13** and the programmable AND gate **450** of FIG. **15** are implemented with the zero-power logic cell **200** of FIG. **2** or the zero-power logic cell **246** of FIG. **6**, and the zero-power memory cell **250** of FIG. **3**. The logic cells **200** or **246** and the electrically erasable and programmable memory cell **250** of the present invention are implemented in CMOS technology without use of a current source. Rather, the logic cells **200** or **246** and the electrically erasable and programmable memory cell **250** of the present invention operate to provide logic levels with zero static power dissipation. Additionally, the logic cells **200** or **246** and the electrically erasable and programmable memory cell **250** of the present invention implemented in CMOS technology are further scalable. Furthermore, the NOR gates and the NAND gates of the programmable OR and AND gates **400** and **450** of FIGS. **13** and **15** may be implemented in CMOS (complementary metal oxide semiconductor) technology with zero power dissipation also such that the programmable OR and AND gates **400** and **450** dissipate zero power.

The foregoing is by way of example only and is not intended to be limiting. For example, any number of corre-

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sponding input signals and logic cells may be used for the programmable OR and AND gates **400** and **450**. In addition, other types of programmable logic devices may be implemented using the logic cells **200** or **246** and the electrically erasable and programmable memory cell **250** of the present invention. Furthermore, the zero-power memory cell **250** of FIG. **8** may be used for any types of applications having an electrically erasable and/or programmable memory cell, aside from just the example of the logic cell **200** and **246** used in programmable logic devices.

Furthermore, any specified voltage levels described herein are by way of example only, and other voltage levels may be used for practicing the present invention, as would be apparent to one of ordinary skill in the art of electronics from the description herein. For example, in the table of FIG. **9**, negative voltages may be used instead of the ground voltage of 0 Volts, or the voltage level for V_{pp} , V_{pp} , or V_{dd} may be different from that used in the table of FIG. **9**. Additionally, the logic cells **200** or **246** and the memory cell **250** may be implemented using other types of P-channel and N-channel field effect transistors aside from just PMOSFETs and NMOSFETs, as would be apparent to one of ordinary skill in the art of electronics from the description herein. The present invention is limited only as defined in the following claims and equivalents thereof.

We claim:

1. An electrically erasable and programmable zero-power memory cell comprising:

- a first variable voltage generator;
- a second variable voltage generator;
- a P-channel sense transistor having a source coupled to said first variable voltage generator;
- an N-channel sense transistor having a source coupled to said second variable voltage generator;
- wherein a drain of said P-channel sense transistor is coupled to a drain of said N-channel sense transistor to form an output of the memory cell;
- and wherein a gate of said P-channel sense transistor is coupled to a gate of said N-channel sense transistor to form a floating gate of the memory cell;
- a write transistor having a source coupled to a WBL (write bit line) and having a gate coupled to a WL (write line);
- a tunneling capacitor coupled between said floating gate of the memory cell and a drain of said write transistor; and
- a coupling capacitor coupled between a CG (control gate) node and said floating gate of the memory cell;
- wherein said CG (control gate) node is biased with a positive voltage during an erase operation and wherein said WBL (write bit line) and said WL (write line) are biased to turn on said write transistor such that a negative voltage forms on said floating gate of the memory cell by charge tunneling through said tunneling capacitor to turn on said P-channel sense transistor for forming a logical high state at said output of said memory cell during said erase operation;
- and wherein said CG (control gate) node is biased with a ground or negative voltage during a program operation and wherein said WBL (write bit line) and said WL (write line) are biased to turn on said write transistor such that a positive voltage forms on said floating gate of the memory cell by charge tunneling through said tunneling capacitor to turn on said N-channel sense transistor for forming a logical low state at said output of said memory cell during said program operation;

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and wherein each of said first and second variable voltage generators applies a positive voltage at said respective source of each of said P-channel and N-channel sense transistors during said erase operation.

2. The electrically erasable and programmable zero-power memory cell of claim **1**, wherein each of said first and second variable voltage generators applies a ground or negative voltage at said respective source of each of said P-channel and N-channel sense transistors during said program operation.

3. The electrically erasable and programmable zero-power memory cell of claim **1**, wherein said P-channel sense transistor is comprised of a PMOSFET (P-channel metal oxide semiconductor field effect transistor), and wherein said N-channel sense transistor and said write transistor are comprised of NMOSFETs (N-channel metal oxide semiconductor field effect transistors).

4. The electrically erasable and programmable zero-power memory cell of claim **1**, wherein a magnitude of the respective threshold voltage of each of said P-channel and N-channel sense transistors is higher than a magnitude of a threshold voltage of standard process P-channel and N-channel transistors.

5. The electrically erasable and programmable zero-power memory cell of claim **4**, wherein a sum of a magnitude of a respective threshold voltage of said P-channel sense transistor and a magnitude of a respective threshold voltage of said N-channel sense transistor is greater than a minimum value in a range of a difference of a first voltage generated by said first voltage generator and a second voltage generated by said second voltage generator during a read operation of said memory cell.

6. The electrically erasable and programmable zero-power memory cell of claim **4**, wherein said magnitude of the respective threshold voltage of each of said P-channel and N-channel sense transistors is adjusted with a thickness of a respective gate oxide and with a concentration of respective channel doping for each of said P-channel and N-channel sense transistors.

7. The electrically erasable and programmable zero-power memory cell of claim **6**, wherein the thickness of the respective gate oxide for each of said P-channel and N-channel sense transistors is for a high voltage MOSFET, and wherein the concentration of the respective channel doping for each of said P-channel and N-channel sense transistors is for a low voltage MOSFET.

8. The electrically erasable and programmable zero-power memory cell of claim **1**, wherein said first variable voltage generator applies a positive voltage on said source of said P-channel sense transistor and *said second variable voltage generator* applies a ground or negative voltage on said source of said N-channel sense transistor, during a read operation.

9. An electrically erasable and programmable zero-power memory cell comprising:

- a first variable voltage generator;
- a second variable voltage generator;
- a P-channel sense transistor having a source coupled to said first variable voltage generator;
- an N-channel sense transistor having a source coupled to said second variable voltage generator;
- wherein a drain of said P-channel sense transistor is coupled to a drain of said N-channel sense transistor to form an output of the memory cell;
- and wherein a gate of said P-channel sense transistor is coupled to a gate of said N-channel sense transistor to form a floating gate of the memory cell;

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a write transistor having a source coupled to a WBL (write bit line) and having a gate coupled to a WL (write line);
 a tunneling capacitor coupled between said floating gate of the memory cell and a drain of said write transistor;
 and
 a coupling capacitor coupled between a CG (control gate) node and said floating gate of the memory cell;
 wherein said CG (control gate) node is biased with a positive voltage during an erase operation and wherein said WBL (write bit line) and said WL (write line) are biased to turn on said write transistor such that a negative voltage forms on said floating gate of the memory cell by charge tunneling through said tunneling capacitor to turn on said P-channel sense transistor for forming a logical high state at said output of said memory cell during said erase operation;
 and wherein said CG (control gate) node is biased with a ground or negative voltage during a program operation and wherein said WBL (write bit line) and said WL (write line) are biased to turn on said write transistor such that a positive voltage forms on said floating gate of the memory cell by charge tunneling through said tunneling capacitor to turn on said N-channel sense transistor for forming a logical low state at said output of said memory cell during said program operation;
 and wherein each of said first and second variable voltage generators applies a ground or negative voltage at said respective source of each of said P-channel and N-channel sense transistors during said program operation.

10. An electrically erasable and programmable zero-power memory cell comprising:
 a P-channel sense transistor having a source coupled to a first voltage generator;
 an N-channel sense transistor having a source coupled to a second voltage generator;
 wherein a drain of said P-channel sense transistor is coupled to a drain of said N-channel sense transistor to form an output of the memory cell;
 and wherein a gate of said P-channel sense transistor is coupled to a gate of said N-channel sense transistor to form a floating gate of the memory cell;
 a write transistor having a source coupled to a WBL (write bit line) and having a gate coupled to a WL (write line);
 a tunneling capacitor coupled between said floating gate of the memory cell and a drain of said write transistor;
 and
 a coupling capacitor coupled between a CG (control gate) node and said floating gate of the memory cell;
 wherein said CG (control gate) node is biased with a positive voltage during an erase operation and wherein said WBL (write bit line) and said WL (write line) are biased to turn on said write transistor such that a negative voltage forms on said floating gate of the memory cell by charge tunneling through said tunneling capacitor to turn on said P-channel sense transistor for forming a logical high state at said output of said memory cell during said erase operation;
 and wherein said CG (control gate) node is biased with a ground or negative voltage during a program operation and wherein said WBL (write bit line) and said WL (write line) are biased to turn on said write transistor such that a positive voltage forms on said floating gate of the memory cell by charge tunneling through said tunneling capacitor to turn on said N-channel sense

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transistor for forming a logical low state at said output of said memory cell during said program operation;
 and wherein a magnitude of the respective threshold voltage of each of said P-channel and N-channel sense transistors is higher than a magnitude of a threshold voltage of standard process P-channel and N-channel transistors.

11. The electrically erasable and programmable zero-power memory cell of claim **10**, wherein a sum of a magnitude of a respective threshold voltage of said P-channel sense transistor and a magnitude of a respective threshold voltage of said N-channel sense transistor is greater than a minimum value in a range of a difference of a first voltage generated by said first voltage generator and a second voltage generated by said second voltage generator during a read operation of the memory cell.

12. The electrically erasable and programmable zero-power memory cell of claim **10**, wherein the thickness of the respective gate oxide for each of said P-channel and N-channel sense transistors is for a high voltage MOSFET, and wherein the concentration of the respective channel doping for each of said P-channel and N-channel sense transistors is for a low voltage MOSFET.

13. An electrically erasable and programmable zero-power memory cell comprising:

a first variable voltage generator;
 a second variable voltage generator;
 a P-channel sense transistor having a source coupled to said first variable voltage generator;
 an N-channel sense transistor having a source coupled to said second variable voltage generator;
 wherein a drain of said P-channel sense transistor is coupled to a drain of said N-channel sense transistor to form an output of the memory cell;
 and wherein a gate of said P-channel sense transistor is coupled to a gate of said N-channel sense transistor to form a floating gate of the memory cell;
 means for forming a negative voltage on said floating gate of the memory cell to turn on said P-channel sense transistor for forming a logical high state at said output of said memory cell during an erase operation;
 means for forming a positive voltage on said floating gate of the memory cell to turn on said N-channel sense transistor for forming a logical low state at said output of said memory cell during a program operation;
 wherein each of said first and second variable voltage generators applies a positive voltage at said respective source of each of said P-channel and N-channel sense transistors during said erase operation.

14. The electrically erasable and programmable zero-power memory cell of claim **13**, wherein each of said first and second variable voltage generators applies a ground or negative voltage at said respective source of each of said P-channel and N-channel sense transistors during said program operation.

15. An electrically erasable and programmable zero-power memory cell comprising:

a first variable voltage generator;
 a second variable voltage generator;
 a P-channel sense transistor having a source coupled to said first variable voltage generator;
 an N-channel sense transistor having a source coupled to said second variable voltage generator;
 wherein a drain of said P-channel sense transistor is coupled to a drain of said N-channel sense transistor to form an output of the memory cell;

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and wherein a gate of said P-channel sense transistor is coupled to a gate of said N-channel sense transistor to form a floating gate of the memory cell;

means for forming a negative voltage on said floating gate of the memory cell to turn on said P-channel sense transistor for forming a logical high state at said output of said memory cell during an erase operation;

means for forming a positive voltage on said floating gate of the memory cell to turn on said N-channel sense transistor for forming a logical low state at said output of said memory cell during a program operation;

wherein a magnitude of the respective threshold voltage of each of said P-channel and N-channel sense transistors is higher than a magnitude of a threshold voltage of standard process P-channel and N-channel transistors.

16. The electrically erasable and programmable zero-power memory cell of claim **15**, wherein a sum of a magnitude of a respective threshold voltage of said P-channel sense transistor and a magnitude of a respective threshold voltage of said N-channel sense transistor is greater than a minimum value in a range of a difference of a first voltage generated by said first voltage generator and a second voltage generated by said second voltage generator during a read operation of the memory cell.

17. The electrically erasable and programmable zero-power memory cell of claim **15**, wherein the thickness of the respective gate oxide for each of said P-channel and N-channel sense transistors is for a high voltage MOSFET, and wherein the concentration of the respective channel doping for each of said P-channel and N-channel sense transistors is for a low voltage MOSFET.

18. A method for erasing and programming an electrically erasable and programmable zero-power memory cell, the method comprising:

applying a first voltage generated by a first variable voltage generator on a source of a P-channel sense transistor;

applying a second voltage generated by a second variable voltage generator on a source of an N-channel sense transistor;

wherein a drain of said P-channel sense transistor is coupled to a drain of said N-channel sense transistor to form an output of the memory cell;

and wherein a gate of said P-channel sense transistor is coupled to a gate of said N-channel sense transistor to form a floating gate of the memory cell;

and wherein a write transistor has a source coupled to a WBL (write bit line), and has a gate coupled to a WL (write line), and has a drain coupled to said floating gate of the memory cell via a tunneling capacitor;

and wherein a coupling capacitor is coupled between a CG (control gate) node and said floating gate of the memory cell;

biasing said CG (control gate) node with a positive voltage during an erase operation and biasing said WBL (write bit line) and said WL (write line) to turn on said write transistor such that a negative voltage forms on said floating gate of the memory cell by charge tunneling through said tunneling capacitor to turn on said P-channel sense transistor for forming a logical high state at said output of said memory cell during said erase operation;

biasing said CG (control gate) node with a ground or negative voltage during a program operation and bias-

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ing said WBL (write bit line) and said WL (write line) to turn on said write transistor such that a positive voltage forms on said floating gate of the memory cell by charge tunneling through said tunneling capacitor to turn on said N-channel sense transistor for forming a logical low state at said output of said memory cell during said program operation; and

applying a positive voltage at said respective source of each of said P-channel and N-channel sense transistors with said first and second variable voltage generators, during said erase operation.

19. The method of claim **18**, further comprising:

applying a ground or negative voltage at said respective source of each of said P-channel and N-channel sense transistors with said first and second variable voltage generators, during said program operation.

20. The method of claim **18**, wherein said P-channel sense transistors is comprised of a PMOSFET (P-channel metal oxide semiconductor field effect transistor), and wherein said N-channel sense transistor and said write transistor are comprised of NMOSFETs (N-channel metal oxide semiconductor field effect transistors).

21. The method of claim **18**, wherein a magnitude of the respective threshold voltage of each of said P-channel and N-channel sense transistors is higher than a magnitude of a threshold voltage of standard process P-channel and N-channel transistors.

22. The method of claim **21**, wherein a sum of a magnitude of a respective threshold voltage of said P-channel sense transistor and a magnitude of a respective threshold voltage of said N-channel sense transistor is greater than a minimum value in a range of a difference of a first voltage generated by said first variable voltage generator and a second voltage generated by said second variable voltage generator during a read operation of said memory cell.

23. The method of claim **22**, wherein said magnitude of the respective threshold voltage of each of said P-channel and N-channel sense transistors is adjusted with a thickness of a respective gate oxide and with a concentration of respective channel doping for each of said P-channel and N-channel sense transistors.

24. The method of claim **23**, wherein the thickness of the respective gate oxide for each of said P-channel and N-channel sense transistors is for a high voltage MOSFET, and wherein the concentration of the respective channel doping for each of said P-channel and N-channel sense transistors is for a low voltage MOSFET.

25. The method of claim **18**, further comprising:

applying a positive voltage on said source of said P-channel sense transistor with said first variable voltage generator and applying a ground or negative voltage on said source of said N-channel sense transistor with said second variable voltage generator, during a read operation.

26. A method for erasing and programming an electrically erasable and programmable zero-power memory cell, the method comprising:

applying a first voltage generated by a first variable voltage generator on a source of a P-channel sense transistor;

applying a second voltage generated by a second variable voltage generator on a source of an N-channel sense transistor;

wherein a drain of said P-channel sense transistor is coupled to a drain of said N-channel sense transistor to form an output of the memory cell;

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and wherein a gate of said P-channel sense transistor is coupled to a gate of said N-channel sense transistor to form a floating gate of the memory cell;

and wherein a write transistor has a source coupled to a WBL (write bit line), and has a gate coupled to a WL (write line), and has a drain coupled to said floating gate of the memory cell via a tunneling capacitor;

and wherein a coupling capacitor is coupled between a CG (control gate) node and said floating gate of the memory cell;

biasing said CG (control gate) node with a positive voltage during an erase operation and biasing said WBL (write bit line) and said WL (write line) to turn on said write transistor such that a negative voltage forms on said floating gate of the memory cell by charge tunneling through said tunneling capacitor to turn on said P-channel sense transistor for forming a logical high state at said output of said memory cell during said erase operation;

biasing said CG (control gate) node with a ground or negative voltage during a program operation and biasing said WBL (write bit line) and said WL (write line) to turn on said write transistor such that a positive voltage forms on said floating gate of the memory cell by charge tunneling through said tunneling capacitor to turn on said N-channel sense transistor for forming a logical low state at said output of said memory cell during said program operation; and

applying a ground or negative voltage at said respective source of each of said P-channel and N-channel sense transistors with said first and second variable voltage generators, during said program operation.

27. A method for erasing and programming an electrically erasable and programmable zero-power memory cell, the method comprising:

applying a first voltage on a source of a P-channel sense transistor;

applying a second voltage on a source of an N-channel sense transistor;

wherein a drain of said P-channel sense transistor is coupled to a drain of said N-channel sense transistor to form an output of the memory cell;

and wherein a gate of said P-channel sense transistor is coupled to a gate of said N-channel sense transistor to form a floating gate of the memory cell;

and wherein a write transistor has a source coupled to a WBL (write bit line), and has a gate coupled to a WL (write line), and has a drain coupled to said floating gate of the memory cell via a tunneling capacitor;

and wherein a coupling capacitor is coupled between a CG (control gate) node and said floating gate of the memory cell;

biasing said CG (control gate) node with a positive voltage during an erase operation and biasing said WBL (write bit line) and said WL (write line) to turn on said write transistor such that a negative voltage forms on said floating gate of the memory cell by charge tunneling through said tunneling capacitor to turn on said P-channel sense transistor for forming a logical high state at said output of said memory cell during said erase operation; and

biasing said CG (control gate) node with a ground or negative voltage during a program operation and biasing said WBL (write bit line) and said WL (write line) to turn on said write transistor such that a positive

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voltage forms on said floating gate of the memory cell by charge tunneling through said tunneling capacitor to turn on said N-channel sense transistor for forming a logical low state at said output of said memory cell during said program operation;

wherein a magnitude of the respective threshold voltage of each of said P-channel and N-channel sense transistors is higher than a magnitude of a threshold voltage of standard process P-channel and N-channel transistors.

28. The method of claim 27, wherein a sum of a magnitude of a respective threshold voltage of said P-channel sense transistor and a magnitude of a respective threshold voltage of said N-channel sense transistor is greater than a minimum value in a range of a difference of a first voltage generated by said first voltage generator and a second voltage generated by said second voltage generator during a read operation of the memory cell.

29. The method of claim 27, wherein the thickness of the respective gate oxide for each of said P-channel and N-channel sense transistors is for a high voltage MOSFET, and wherein the concentration of the respective channel doping for each of said P-channel and N-channel sense transistors is for a low voltage MOSFET.

30. A method for fabricating an electrically erasable and programmable zero-power memory cell, the method comprising:

forming a P-channel sense transistor having a source coupled to a first voltage generator;

forming an N-channel sense transistor having a source coupled to a second voltage generator;

wherein a drain of said P-channel sense transistor is coupled to a drain of said N-channel sense transistor to form an output of the memory cell;

and wherein a gate of said P-channel sense transistor is coupled to a gate of said N-channel sense transistor to form a floating gate of the memory cell;

performing a first channel doping implantation for implanting a P-type channel dopant into an N-channel region of said N-channel sense transistor;

wherein said a first concentration of said P-type channel dopant implanted into said N-channel region of said N-channel sense transistor is for a low voltage NMOSFET;

performing a second channel doping implantation for implanting an N-type channel dopant into a P-channel region of said P-channel sense transistor;

wherein said a second concentration of said N-type channel dopant implanted into said P-channel region of said P-channel sense transistor is for a low voltage PMOSFET;

forming an N-channel gate oxide over said N-channel region of said N-channel sense transistor;

wherein a first thickness of said N-channel gate oxide has a thickness of a gate oxide for a high voltage NMOSFET; and

forming a P-channel gate oxide over said P-channel region of said P-channel sense transistor;

wherein a second thickness of said P-channel gate oxide has a thickness of a gate oxide for a high voltage PMOSFET.

31. The method of claim 30, further comprising:

forming a write transistor having a source coupled to a WBL (write bit line) and having a gate coupled to a WL (write line);

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forming a tunneling capacitor coupled between said floating gate of the memory cell and a drain of said write transistor; and

forming a coupling capacitor coupled between a CG (control gate) node and said floating gate of the memory cell;

wherein said CG (control gate) node is biased with a positive voltage during an erase operation and wherein said WBL (write bit line) and said WL (write line) are biased to turn on said write transistor such that a negative voltage forms on said floating gate of the memory cell by charge tunneling through said tunneling capacitor to turn on said P-channel sense transistor for forming a logical high state at said output of said memory cell during said erase operation;

and wherein said CG (control gate) node is biased with a ground or negative voltage during a program operation and wherein said WBL (write bit line) and said WL (write line) are biased to turn on said write transistor such that a positive voltage forms on said floating gate of the memory cell by charge tunneling through said tunneling capacitor to turn on said N-channel sense transistor for forming a logical low state at said output of said memory cell during said program operation.

32. *An electrically erasable and programmable zero-power memory cell comprising:*

a first variable voltage generator;

a second variable voltage generator;

a P-channel sense transistor having a source coupled to said first variable voltage generator;

an N-channel sense transistor having a source coupled to said second variable voltage generator;

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wherein a drain of said P-channel sense transistor is coupled to a drain of said N-channel sense transistor to form an output of the memory cell;

and wherein a gate of said P-channel sense transistor is coupled to a gate of said N-channel sense transistor to form a floating gate of the memory cell.

33. *The memory cell of claim 32, wherein said first and second variable voltage generators apply a ground or negative voltage at said respective sources of said P-channel and N-channel sense transistors during programming of the memory cell.*

34. *The memory cell of claim 32, wherein said first and second variable voltage generators apply a positive voltage at said respective sources of said P-channel and N-channel sense transistors during erasing of the memory cell.*

35. *The memory cell of claim 32, wherein said first variable voltage generator applies a positive voltage at said source of said P-channel sense transistor and said second variable voltage generator applies a ground or negative voltage at said source of said N-channel sense transistor during reading of the memory cell.*

36. *The memory cell of claim 32, wherein a magnitude of the respective threshold voltages of said P-channel and N-channel sense transistors is higher than a magnitude of the respective threshold voltages of standard process P-channel and N-channel transistors.*

37. *The memory cell of claim 32, wherein said first and second variable voltage generators comprise voltage sources.*

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