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(54) **A NOT circuit**

Ein NOT-Schaltkreis

Un circuit NOT

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- **PATENT ABSTRACTS OF JAPAN vol. 1998, no. 04, 31 March 1998 (1998-03-31) -& JP 09 326514 A (FUJITSU LTD; HITACHI LTD; KOKUSAI CHODENDO SANGYO GIJUTSU KENKYU CENTE), 16 December 1997 (1997-12-16)**
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Description

Technical Field

5 **[0001]** The present invention relates to a point contact array comprising a plurality of devices in each of which a point contact is formed or disconnected between electrodes facing each other to control conductance, a NOT circuit, and an electronic circuit using the same, and more particularly to a NOT circuit comprising an electronic device (an atomic switch which will be described below) in which a point contact is formed or disconnected between electrodes facing each other to control conductance, and an electronic circuit using the same.

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Background Art

[0002] As related arts [1], methods for forming a point contact to control conductance are disclosed by, for example, J. K. Gimzewski and R. Moller: Phys. Rev. B36, p1284, 1987, J. L. Costa-Kramer, N. Garcia, P. Garcia-Mochales, P. A. Serena, M. I. Marques, and A. Corrcia: Phys. Rev. B55, p5416, 1997, and H. Ohnishi, Y. Kondo, and K. Takayanagi: Nature, Vol. 395, p780, 1998.

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[0003] Each of these methods requires a piezo device in order to form and control each point contact. In other words, a metallic probe equipped with the piezo device is positioned with respect to an opposite electrode with high precision by driving the piezo device, thus forming a point contact between the probe and the opposite electrode. The state thereof is controlled.

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[0004] In addition to these arts, as a related art [2], a method for controlling conductance of each point contact, the method using organic molecules is disclosed by C. P. Collier et al.: Science, Vol. 285, p391, 1999.

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[0005] According to this method, the conductivity of rotaxane molecules of one molecule thickness sandwiched by electrodes facing each other is changed by applying high voltage between the electrodes. In other words, the rotaxane molecules, sandwiched between the electrodes, initially exhibit the conductivity. When a predetermined or higher voltage of a certain polarity is applied, the molecules are oxidized to reduce the conductivity, so that the electrodes are isolated from each other.

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[0006] [3] Hitherto, it is known that an AND circuit and an OR circuit can be formed using a diode serving as a two-terminal device.

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[0007] On the other hand, it is also well-known that a NOT circuit cannot be formed using only the diode. In other words, the NOT circuit cannot be formed using only the conventional two-terminal devices. Accordingly, the formation of the NOT circuit requires a transistor serving as a three-terminal device.

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[0008] All of logic circuits can be constructed using the combination of the AND circuit, the OR circuit, and the NOT circuit. In other words, a three-terminal circuit is indispensable to the formation of an arbitrary logic circuit. This fact is described in detail in, for example, "NYUMON ELECTRONICS KOHZA (Library of Introduction to Electronics) Digital Circuit", Vol. 2, pages 1 to 7, published by Nikkan Kogyo Shinbun Co., Ltd. (I).

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[0009] Nowadays as the integration of silicon devices is approaching its limit, new nanometer-sized devices such as molecular devices are being developed. For example, the result of the experiment of a transistor using a carbon nanotube is described in Nature, Vol. 393, pages 49 to 50, 1998 (II).

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[0010] According to the method of the foregoing related arts [1], however, one point contact needs at least one piezo device and a complicated control circuit for driving the device. It is very difficult to integrate these components.

[0011] According to the method of the foregoing related art [2], since temporarily oxide molecules are reduced and the conductivity cannot be restored, the application is remarkably restricted. Further, for [3], the foregoing three-terminal circuit becomes a factor to inhibit miniaturization.

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[0012] For example, according to the method of the foregoing document (II), a structure such as a gate other than the carbon nanotube is formed by applying an existing process for manufacturing a semiconductor device. Accordingly, the size of the entire transistor is not so different from that of the conventional transistor. In other words, actually, the development of nanometer-sized devices still remains in the stage of demonstrations of the fundamental principle.

[0013] A prior art document entitled "Quantum point contact switch realised by solid electrochemical reaction" by TERABE K et al on pages 7 and 8 of the RIKEN Review, Institute of Physical and Chemical Research, Wako, Japan, No. 37, July 2001 (2001-07), XP-002287674 discloses the principles of the formation and annihilation of a quantum point contact which is controlled by a solid electrochemical reaction.

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[0014] The present invention seeks to provide an improved NOT circuit.

[0015] According to the present invention as defined by claim 1, there is provided a NOT circuit which comprises a first electrode made of a compound conductive material having ionic conductivity and electronic conductivity and a second electrode made of a conductive substance and spaced apart from the first electrode, wherein conductance between the first and second electrodes is controlled by forming a bridge of metal atoms between the first and second electrodes

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- [0016] Preferably the compound conductive material is Ag_2S , Ag_2Se , Cu_2S , or Cu_2Se .
[0017] Conveniently the NOT circuit comprises a resistor and a capacitor, each of which serves as a two-terminal device.
[0018] Advantageously the NOT circuit comprises a diode in addition to the resistor and the capacitor.
[0019] Preferably a voltage to be applied to the first and second electrodes is controlled through the capacitor to control the conductance between the first and second electrodes.

Brief Description of the Drawings

[0020]

Fig. 1 is a schematic perspective view showing a point contact array, in which a plurality of point contacts are arranged.

Fig. 2 is a schematic view showing a point contact array constituting a multiple storage memory.

Fig. 3 shows the result of reading of the multiple storage memory according to a first example.

Fig. 4 shows the result of an arithmetic operation by an adding circuit comprising a point contact array according to a second example.

Fig. 5 shows the result of an arithmetic operation by a subtracting circuit comprising a point contact array according to a third example.

Fig. 6 is a schematic diagram of an OR gate comprising a point contact array according to a fourth example.

Fig. 7 shows the results of the operation of an OR gate comprising a point contact array according to the fourth example.

Fig. 8 is an equivalent circuit diagram of a point contact array logic circuit according to the fourth example.

Fig. 9 is a schematic diagram of an AND gate comprising a point contact array according to a fifth example.

Fig. 10 shows the results of the operation of the AND gate comprising the point contact array according to a fifth example.

Fig. 11 is a view showing a method for forming a point contact array according to a sixth example.

Fig. 12 is a schematic view of a point contact array according to a seventh example, the point contact array controlling the conductivities of semiconductors.

Fig. 13 is a schematic view of a point contact array according to an eighth example, the point contact array having electrodes partially covered with a compound conductor.

Fig. 14 is a schematic diagram of a NOT circuit according to a first embodiment of the present invention.

Fig. 15 includes graphs showing a principle of the operation of the NOT circuit according to the first embodiment of the present invention.

Fig. 16 is a schematic diagram of a NOT circuit according to a second embodiment of the present invention.

Fig. 17 includes graphs showing a principle of the operation of the NOT circuit according to the second embodiment of the present invention.

Fig. 18 is a schematic diagram of a NOT circuit according to a third embodiment of the present invention.

Fig. 19 includes graphs showing a principle of the operation of the NOT circuit according to the third embodiment of the present invention.

Fig. 20 is a schematic diagram of a NOT circuit according to a fourth embodiment of the present invention.

Fig. 21 is a schematic diagram of a one-digit binary adder.

Fig. 22 is a diagram showing logical symbols of the one-digit binary adder.

5 Fig. 23 is a diagram showing a truth table of the one-digit binary adder.

[0021] Embodiments of the present invention will be described in detail hereinbelow with reference to the drawings.

[0022] Fig. 1 is a schematic perspective view showing a point contact array, in which a plurality of point contacts are arranged.

10 **[0023]** As shown in Fig. 1, point contacts (bridges) 6 and 7 each comprising mobile ions (atoms) 5 are formed at the intersections of a metallic wire (first electrode) 2 and metallic wires (second electrodes) 3 and 4, the metallic wire 2 being covered with an electronic/ionic mixed conductor 1. These components are arranged on an insulating substrate 8 and are then fixed thereto using an insulating material (not shown).

15 **[0024]** When a semiconductor or insulator material is interposed between the first and second electrodes, mobile ions are dissolved into the semiconductor or insulator to change the conductance of the semiconductor.

[0025] Consequently, the conductance between the electrodes is changed. The amount of change depends on the amount of the mobile ions dissolved in the semiconductor or insulator material.

20 **[0026]** For the sake of simplification, Fig. 1 shows the point contact array comprising the one metallic wire (first electrode) 2, covered with the electronic/ionic mixed conductor 1, and the two metallic wires (second electrodes) 3 and 4. The number of point contacts is obtained by multiplying the number of metallic wires each constituting the electrode. In this case, 2×1 , namely, two point contacts are formed. When the number of metallic wires constituting the first and second electrodes is increased, a point contact array having $n \times n$ point contacts can be formed.

25 **[0027]** A voltage is applied between the first electrode 2 and the second electrodes 3 and 4, resulting in the formation or disappearance of the bridges 6 and 7 comprising ion atoms. Thus, the conductance of each point contact formed between the electrodes is controlled. Specifically, when a proper negative voltage is applied to the second electrodes 3 and 4 with respect to the first electrode 2, mobile ions (atoms) in the electronic/ionic mixed conductive material are precipitated due to effects of voltage and current, resulting in the formation of the bridges 6 and 7 between the electrodes. Consequently, each conductance between the electrodes is increased. On the other hand, when a proper positive voltage is applied to the second electrodes 3 and 4, the mobile ions (atoms) return to the electronic/ionic mixed conductive material, resulting in the disappearance of the bridges 6 and 7. In other words, the conductance is reduced.

30 **[0028]** As mentioned above, a voltage applied to each metallic wire is independently controlled, so that a voltage applied to the point contact formed at each of the intersections of the first electrode 2 and the second electrodes 3 and 4 can be independently controlled. In other words, the conductance of the point contact at each intersection can be independently controlled.

35 **[0029]** In this manner, an electronic device such as a memory device or an arithmetic device comprising a point contact array and an electric circuit comprising the electronic devices can be formed.

[0030] Examples using a first electrode comprising an electronic/ionic mixed conductive material of Ag_2S and an Ag which is a source of mobile ions of Ag and second electrodes comprising Pt will now be described hereinbelow. It is needless to say that the similar results can be obtained using other materials.

40 **[0031]** When there are about ten atoms of Ag, each bridge can be sufficiently formed. On the basis of the measurement result, on condition that a voltage is 100 mV and initial interelectrode resistance is 100 k Ω , the time required to derive ten Ag atoms from Ag_2S serving as the electronic/ionic mixed conductor, namely, the time required to form a bridge is estimated to be tens of nanoseconds at most. An electric power required to form the bridge is on the order of nanowatts, namely, the power is small. Accordingly, the application of embodiments of the present invention realize the construction of a high-speed device with low power consumption.

45 **[0032]** A first example will now be described.

[0033] Fig. 2 shows a schematic view of a point contact array, the point contact array being applied to a multiple memory device.

50 **[0034]** For the sake of simplification, a sample comprising two point contacts is used in a manner similar to Fig. 1. In this case, Ag_2S is used as an electronic/ionic mixed conductive material 11 functioning as a first electrode and an Ag wire is used as a metallic wire 10. Pt wires are used as metallic wires 13 and 14 each functioning as a second electrode. The first electrode is grounded and voltages V1 and V2 are independently applied to the second electrodes 13 and 14, respectively. When negative voltages are used as V1 and V2, Ag atoms 12 contained in the electronic/ionic mixed conductive material 11 are precipitated to form bridges 15 and 16. When positive voltages are used as V1 and V2, the Ag atoms 12 in the bridges 15 and 16 return to the electronic/ionic mixed conductive material 11, resulting in the disappearance of the bridges 15 and 16. Japanese Patent Application No. 2000-265344, by the inventors of the present application, proposes the detailed mechanism.

55 **[0035]** The use of a plurality of point contacts realizes a new function, which will be described hereinbelow.

[0036] According to the present example, pulse voltages are applied to control the conductance of each point contact. In other words, in order to increase the conductance, a voltage of 50 mV is applied for 5 ms. In order to reduce the conductance, a voltage of -50 mV is applied for 5 ms. Thus, transition in the quantized conductance of each point contact is realized. In other words, the transition corresponds to the writing operation of the memory.

[0037] In order to read a recording state, V1 and V2 are set to 10 mV so that the recorded conductance is not changed by the reading operation. In this situation, current I_1 and I_2 flowing through the metallic wires 13 and 14, each functioning as the second electrode of the point contact, are measured. Fig. 3 shows the result.

[0038] Referring to Fig. 3, I_1 is shown by a thin solid line and I_2 is shown by a thick solid line. The point contact 15 or 16 is subjected to the writing operation every second. The recording state is read out after each writing operation. The ordinate axis on the left denotes a current actually measured. The ordinate axis on the right denotes quantized conductance corresponding thereto. The conductance is obtained by dividing the measured current by the applied voltage (10 mV).

[0039] It is understood from the graph that the conductance of each point contact is quantized. In other words, when it is assumed that N_1 denotes the quantum number of the quantized conductance of a first point contact serving as the bridge 15 and N_2 denotes the quantum number of the quantized conductance of a second point contact serving as the bridge 16, $N_1 = 0$ to 3 and $N_2 = 0$ to 3, namely, 16 recording states are realized in total.

[0040] Four quantized states of $N = 0$ to 3 are used. If a state having a larger quantum number is used, the recording density can be increased. It is needless to say that the recording density can also be increased by increasing the number of point contacts.

[0041] A second example will now be described.

[0042] First, an example in which an adding circuit is realized with the configuration shown in the first example will be described.

[0043] Inputs denote the quantum numbers N_1 and N_2 of the quantized conductance of the point contacts serving as the bridges 15 and 16. The input operation is performed by controlling the voltages V1 and V2 to set each of N_1 and N_2 to a desired value. V1 and V2 are set to a reading voltage, for example, 10 mV and a current I_{out} flowing from the first electrode 10 to a ground potential is measured, thus obtaining the result of an arithmetic operation.

[0044] Fig. 4 shows the result of the arithmetic operation according to the second example. Below a graph, the inputted N_1 and N_2 and measured N_{out} are shown so as to correspond to the abscissa axis of the graph. It is found that the obtained current I_{out} has quantized conductance corresponding to $(N_1 + N_2)$. In other words, the addition is correctly performed. According to the present embodiment, 16 addition results corresponding to $N_1 = 0$ to 3 and $N_2 = 0$ to 3 are shown in the same way as the first embodiment. Larger quantum numbers can also be used. For the number of point contacts used, namely, the number of inputs, three or more inputs can also be used.

[0045] A third example will now be described.

[0046] The configuration shown in the first example can also be applied to a subtracting circuit. Inputs are controlled by the same method described in the second example. Upon subtraction, voltages, which have the same absolute value and whose polarities are opposite to each other, can be used as V1 and V2. For example, when V1 is set to 10 mV and V2 is set to -10 mV, the current I_{out} corresponding to quantized conductance, which corresponds to $(N_1 - N_2)$, flows from the first electrode to the ground potential. At that time, when the current flows in the direction from the first electrode to the ground potential, the result of the arithmetic operation indicates a positive value. When the current flows in the direction from the ground potential to the first electrode, the result of the arithmetic operation indicates a negative value.

[0047] Fig. 5 shows the result of the arithmetic operation according to the third example.

[0048] The arithmetic operation of $(N_1 - N_2)$ is correctly performed. Further, if three or more point contacts are used, an arithmetic operation of $(N_1 + N_2 - N_3)$ can be performed at a time. In this case, for example, on condition that V1 and V2 are set to 10 mV and V3 is set to -10 mV, the arithmetic operation can be performed.

[0049] A fourth example will now be described.

[0050] According to the present example, a logic circuit is constructed using the point contacts. For the configuration of the logic circuit, in contrast to the first to third example, the transition in the quantized conductance of each point contact is not used. In other words, the point contact is used as an on-off switching device. Typically, a resistance in the ON state is equal to or less than 1 k Ω and a resistance in the OFF state is equal to or more than 100 k Ω .

[0051] Fig. 6 is a schematic diagram of an OR gate formed using the point contacts.

[0052] Ag wires 21 and 22 are covered with Ag₂S 23 and 24, respectively, thus forming first electrodes. Ag bridges 25 and 26, formed on the Ag₂S 23 and 24, face a Pt electrode 20 serving as a second electrode, thus forming point contacts. One end of the Pt electrode 20 is connected to a reference voltage V_s through a resistance 27 (10 k Ω in the present example) and the other end functions as an output terminal to generate an output voltage V_{out} . Input voltage V1 and V2 are applied to the Ag wires 21 and 22, resulting in the formation or disappearance of the bridges 25 and 26. Thus, each point contact functions as an on-off switching device.

[0053] Fig. 7 shows the results of the operation. According to the present example, the inputs, namely, V1 and V2 are changed every second to measure the output V_{out} .

[0054] In a two-input OR gate, for binary low-level and high-level inputs, if either input indicates a high level, an output must go to a high level.

[0055] The OR gate is operated using 0 V (the reference potential V_s also has the same value) as a low-level input and 200 mV as a high-level input. Fig. 7(a) shows the result of this case.

[0056] When either one of the two inputs V_1 and V_2 is 200 mV, the output V_{out} substantially indicates 200 mV. The normal operation is found from the graph. When a high-level voltage is increased to 500 mV, the similar result (Fig. 7 (b)) is obtained.

[0057] Fig. 8 is an equivalent circuit diagram of the present logic circuit.

[0058] The reference voltage V_s and the input voltages V_1 and V_2 cause the formation or disappearance of the bridges 25 and 26 (Fig. 6), resulting in a change in the resistance of each of resistors R_1 and R_2 (resistances of the point contacts formed by the bridges). Although there is a small resistance R_{12} (about several ohms to tens of ohms) between two point contacts on the electrode 20 (Fig. 6), the resistance is negligible as compared to R_0 (10 k Ω), and R_1 and R_2 (1 k Ω to 1 M Ω).

[0059] First, when both of V_1 and V_2 are 0 V, all of the three voltages connected to the system indicate 0 V. Therefore, the output V_{out} necessarily indicates 0 V. Subsequently, when V_1 is 0 V and V_2 is 200 mV (500 mV), the bridge 25 (Fig. 6) grows and the resistance of the resistor R_2 decreases. Typically, the resistance is equal to or less than 1 k Ω .

[0060] Consequently, since the resistance of R_2 is an order or more of magnitude smaller than that of R_0 , V_2' indicates about 200 mV (500 mV). At this time, since V_1' also indicates about 200 mV (500 mV), a voltage whereby a bridge disappears is applied to the bridge 26 (Fig. 6), so that R_1 indicates a large value of 1 M Ω or higher. Consequently, when V_1 is 0 V, $R_0, R_1 \gg R_2$. Accordingly, V_1' indicates about 200 mV (500 mV) that is equivalent to V_2' . Thus, the output indicates 200 mV (500 mV). To be precise, the growth of the bridge 25 and the disconnection of the bridge 26 simultaneously occur, thus causing the above-described result.

[0061] In a case where V_1 is 200 mV (500 mV) and V_2 is 0 V, the similar explanation can be applied to the case. When both of V_1 and V_2 are 200 mV (500 mV), both of the bridges 25 and 26 grow. Consequently, the voltage of V_1 and V_2 , namely, 200 mV (500 mV) is generated.

[0062] A fifth example now be described.

[0063] According to the present example, the configuration of an AND gate will be described with reference to Fig. 9.

[0064] According to the present example, one end of an Ag wire 30, covered with an Ag_2S thin film 31, is connected to a reference voltage V_s through a resistor 37. The other end is an output terminal. Bridges 33 and 34, formed by precipitation of Ag atoms serving as mobile ions, are formed so as to face two Pt electrodes 35 and 36, respectively. Input voltages V_1 and V_2 are applied to the two Pt electrodes 35 and 36. In Fig. 9, reference numeral 32 denotes an Ag ion in the Ag_2S thin film 31.

[0065] Fig. 10 shows the results of the arithmetic operation of the AND gate. In the two-input AND gate, when both of the two inputs are at a high level, an output V_{out} goes to a high level.

[0066] Fig. 10(a) shows the result of the operation on condition that the high level is set to 200 mV. In this instance, a reference voltage is also set to 200 mV.

[0067] Fig. 10(b) shows the result of the operation on condition that the high level is set to 500 mV. In this instance, the reference voltage is 500 mV.

[0068] Referring to Fig. 10, when the high level is set to 200 mV, V_1 is 0V, and V_2 is 200 mV, the output V_{out} indicates a partial value (about 50 mV). However, in the other cases, the output indicates 0 V as the low level or 200 mV as the high level. When the high level is set to 500 mV, the normal operation is performed in all of input patterns. In the case of the operation using 200 mV, when a critical voltage to determine low-high levels is set to 100 mV, no problem occurs. The cause will be described below.

[0069] The principle of the operation of the AND gate will be described again with reference to Fig. 8. According to the present example, the reference voltage V_s is at the high level (200 or 500 mV). First, when both of V_1 and V_2 are 0 V, both of the bridges 33 and 34 (Fig. 9) grow. Thus, the resistance of each of the resistors R_1 and R_2 is typically equal to or less than 1 k Ω . In other words, the input voltages at the low level are connected to the output terminal through resistances which are one order or more of magnitude smaller than the resistance R_0 (10 k Ω). Accordingly, the output V_{out} indicates 0 V. Subsequently, when V_1 is 0 V and V_2 is 200 mV (500 mV), the bridge 33 (Fig. 9) alone grows.

[0070] On the other hand, in the bridge 34, the voltage V_2' is smaller than 200 mV (500 mV) due to the voltage V_1 . In other words, the voltage of a polarity, which allows the bridge to disappear, is applied to the bridge 34, resulting in the disappearance of the bridge 34. The resistance of R_2 is increased to about 1 M Ω . In this instance, when a potential difference between V_2' and V_2 is small, the bridge disappears insufficiently. Therefore, the resistance of R_2 is not increased enough. Accordingly, the above-mentioned partial output may be generated. However, when a high-level voltage is set to 500 mV, the potential difference between V_2' and V_2 is increased enough. Thus, the completely normal operation is realized.

[0071] The same description applies in the case where V_1 is 200 mV (500 mV) and V_2 is 0 V. Since the characteristics of the bridges 33 and 34 each constituting the point contact are slightly different from each other, a normal output is

obtained in the case where an operating voltage is 200 mV. Finally, when both of V1 and V2 are 200 mV (500 mV), the formation or disappearance of the bridges 33 and 34 does not occur. Since all of voltages are 200 mV (500 mV), an output voltage also indicates 200 mV (500 mV).

[0072] The logic circuits using the point contacts have been described. According to the foregoing examples the two-input logic circuits have been explained. When three or more point contacts are used, a logic circuit having three or more inputs can be formed on the basis of the above-mentioned principle of operation.

[0073] A sixth example will now be described.

[0074] A method for forming a point contact array will be described.

[0075] Fig. 11 is a diagram showing the method for forming a point contact array according to the sixth example of the present invention.

[0076] As shown in Fig. 11, Ag wires 41 and 42 are formed on an insulating substrate 40. The surfaces of the Ag wires are sulfurized to form Ag_2S films 43 and 44. Pt wires 45 and 46 are disposed thereon. Thus, an essential part of the point contact array is completed. It is important that bridges 47 and 48 comprising Ag atoms are formed at the intersections of the Ag wires 41 and 42 and the Pt wires 45 and 46, the Ag wires 41 and 42 being covered with the Ag_2S films 43 and 44, respectively.

[0077] Therefore, when the Pt wires 45 and 46 are arranged, a voltage is applied between the Pt wires 45 and 46 and the Ag wires 41 and 42 to precipitate Ag on the Ag_2S film 43 and 44, resulting in the formation of the bridges 47 and 48. Consequently, when the Pt wires 45 and 46 are arranged using, for example, a wiring system or the like, embodiments of the present invention can be realized.

[0078] The bridge can be previously formed at each intersection by evaporation of Ag through a mask. Alternatively, electron beams can be irradiated on each Ag wire covered with the Ag_2S film to precipitate Ag atoms. It is important that Ag exists between Ag_2S functioning as a first electrode and Pt functioning as a second electrode.

[0079] Furthermore, Pt wires can be previously formed on another substrate and be then adhered to the substrate having the Ag wires covered with the Ag_2S films.

[0080] A seventh example now be described.

[0081] A method for forming another point contact array and the structure thereof will be described.

[0082] Fig. 12 is a schematic view of a point contact array according to the seventh example; the point contact array controlling the conductivity of each semiconductor.

[0083] Referring to Fig. 12, Ag wires 51 and 52, respectively covered with Ag_2S films 53 and 54, are formed on an insulating substrate 50. Further, semiconductors or insulators 57, 58, 59, and 60, which can dissolve Ag atoms, are formed only at the intersections of the Ag wires 51 and 52 and the Pt wires 55 and 56. In Fig. 12, an insulating material covering these components are not shown. All of the components shown in the diagram are embedded in a device.

[0084] In this case, according to the same principle as that described above, Ag ions move from the Ag_2S films 53 and 54. The moving Ag ions are dissolved into the semiconductors or insulators 57, 58, 59, and 60 to change the conductivity of each semiconductor or insulator. Thus, the similar effects as those in the above-mentioned embodiments can be realized. In this case, since a space where the formation or disappearance of the bridges is not needed in the device, these components can be easily embedded in an insulating member.

[0085] When Ag thin films are previously formed in place of the semiconductors or insulators, the same structure as that described in the sixth example is obtained. In this case, Ag atoms contained in the Ag thin films enter the Ag_2S films, resulting in the disappearance of the thin film.

[0086] Crystals or amorphous materials of GeS_x , GeSe_x , GeTe_x , or WO_x ($0 < x < 100$) are used as the semiconductors or insulators which can dissolve the Ag ions.

[0087] An eighth example will now be described.

[0088] Fig. 13 shows an example in which a part of each metallic wire serving as a first electrode is covered with an electronic/ionic mixed conductor. According to the present example, it is enough to form point contacts, each comprising "a metal serving as a first electrode, an electronic/ionic mixed conductor, a bridge or a semiconductor, and a metal serving as a second electrode", at the intersections of the metallic wire functioning as the first electrode and metallic wires each functioning as the second electrode.

[0089] Therefore, as shown in Fig. 13, when electronic/ionic mixed conductors 73 and 74 are formed only in the vicinity of the intersections of a metallic wire 70 functioning as a first electrode and metallic wires 71 and 72 each functioning as a second electrode, a point contact (bridge) 75 can be formed between the electronic/ionic mixed conductor 73 and the metallic wire 71 and a point contact (bridge) 76 can be formed between the electronic/ionic mixed conductor 74 and the metallic wire 72.

[0090] Furthermore, for the metal serving as the first electrode, each part which is in contact with the electronic/ionic mixed conductor can be different from a material of the wire between the point contacts. According to the present example, for example, Ag wires 79 and 80 are used as parts which are in contact with electronic/ionic mixed conductors (Ag_2S) 77 and 78, respectively. Tungsten wires are used as other parts 81 to 83. For the material of each part to be in contact with the electronic/ionic mixed conductor, it is necessary that each part comprise the same element as the mobile

ions in the electronic/ionic mixed conductor. According to the present example, therefore, since Ag_2S is used as the electronic/ionic mixed conductor, Ag is used as a material for the part which is in contact therewith.

[0091] A NOT circuit according to an embodiment of the present invention and an electronic circuit using the same will now be described in detail hereinbelow.

[0092] Fig. 14 is a schematic diagram of a NOT circuit according to a first embodiment of the present invention.

[0093] As shown in the diagram, a first electrode 102 serving as an electronic/ionic mixed conductor is formed on a conductive substance 101. A potential difference between the first electrode 102 and a second electrode 103 is controlled, thus controlling so that mobile ions (atoms) 104 in the electronic/ionic mixed conductor are precipitated as metallic atoms on the surface of the first electrode 102, alternatively, the precipitated metallic atoms are dissolved as mobile ions (atoms) into the first electrode 102. In other words, when a proper negative voltage is applied to the second electrode 103 with respect to the first electrode 102, the mobile ions (atoms) 104 in the electronic/ionic mixed conductive material is precipitated due to the effect of voltage and current, thus forming a bridge 105 between the electrodes 102 and 103. Consequently, resistance between the electrodes 102 and 103 decreases.

[0094] On the contrary, when a proper positive voltage is applied to the second electrode 103, the mobile ions (atoms) 104 are dissolved into the electronic/ionic mixed conductive material, resulting in the disappearance of the bridge 105. In other words, the resistance increases. Hereinbelow, such a two-terminal device will be called an "atomic switch". Japanese Patent Application No. 2000-265344, by the inventors of the present application, proposes the detailed principle of operation thereof.

[0095] A voltage $V_{H/2}$ corresponding to a high-level output is applied to the second electrode 103 of the atomic switch through a resistor 106 (resistance R_1). An input terminal V_{in} is connected to the second electrode 103 through a capacitor 108 (capacitance C_1). On the other hand, a voltage V_L corresponding to a low-level output is applied to the conductive substance 101 functioning as the first electrode 102 of the atomic switch through a resistor 107 (resistance R_2). An output terminal V_{out} is connected to the conductive substance 101.

[0096] It is assumed that $R(\text{ON})$ denotes a resistance of the atomic switch in the ON state and $R(\text{OFF})$ denotes a resistance thereof in the OFF state. The resistors and the atomic switch which satisfy the following relation are used.

$$R(\text{OFF}) \gg R_2 \gg R(\text{ON}) \sim R_1$$

[0097] For the input V_{in} , V_H is used as a high-level input and V_L is used as a low-level input. When the input V_{in} is V_L , the output V_{out} indicates $V_{H/2}$. When the input V_{in} is V_H , the output V_{out} indicates V_L . In other words, when the input is at a high level, the output goes to a low level. When the input is at a low level, the output goes to a high level. Thus, the atomic switch functions as a NOT circuit.

[0098] Hereinbelow, an embodiment using an atomic switch, in which Ag_2S formed on Ag is used as the first electrode 102 and Pt is used as the second electrode 103, will now be described. It is needless to say that a NOT circuit can be formed using an atomic switch having another electronic/ionic mixed conductor such as Ag_2Se , Cu_2S , or Cu_2Se and a metal other than Pt.

[0099] As mentioned above, the use of the atomic switch, serving as a two-terminal device comprising the first electrode 102 made of an electronic/ionic mixed conductive material and the second electrode 103 made of a conductive substance, realizes a NOT circuit comprising only the two-terminal devices.

[0100] In this instance, the case where V_H is used as the high-level input V_{in} and V_L (0 V) is used as the low-level input will be used as an example and the principle of operation of the NOT circuit shown in Fig. 14 will now be described in detail with reference to Fig. 15.

[0101] When the input V_{in} changes from a low level (V_L) to a high level (V_H) at time t_1 [refer to Fig. 15(a)], charges $Q = C_1 \times V_H$ (C_1 denotes the capacitance of the capacitor) are accumulated in the capacitor 108. At this time, a potential V_{in}' of the second electrode 103 of the atomic switch changes due to a current, which temporarily flows, as shown in Fig. 15(b). In other words, the potential of the second electrode 103 of the atomic switch is temporarily higher than that of the first electrode 102, so that the atomic switch changes to the OFF state (high resistance) [refer to Fig. 15(c)]. Thus, $R(\text{OFF}) \gg R_2$. The output V_{out} indicates V_L [refer to Fig. 15(d)].

[0102] Since the resistance of the atomic switch is increased, the potential between the electrodes 102 and 103 of the atomic switch is increased as shown in Fig. 15(e). Switching time t_s is almost determined by the capacitance C_1 of the capacitor 108 and the resistance R_1 of the resistor 106. For instance, when it is assumed that the capacitance C_1 of the capacitor is 1 pF and the resistance R_1 is 10 Ω , switching can be performed on the order of gigahertz.

[0103] On the other hand, when the input V_{in} changes from the high level (V_H) to the low level (V_L) at time t_2 [refer to Fig. 15(a)], the charges accumulated in the capacitor 108 are discharged. Due to a current which temporarily flows, the potential V_{in}' of the second electrode 103 of the atomic switch changes as shown in Fig. 15(b). In other words, the potential of the second electrode 103 in the atomic switch is temporarily remarkably lower than that of the first electrode

102, so that the atomic switch changes to the ON state (low resistance) [refer to Fig. 15(c)]. Consequently, $R_2 \gg R(\text{ON})$. The output V_{out} indicates $VH/2$ [refer to Fig. 15(d)].

5 [0104] Fig. 15(e) shows the potential difference between the electrodes 102 and 103 of the atomic switch. When the input V_{in} is at the low level (VL), the potential difference between the electrodes 102 and 103 of the atomic switch indicates about zero. Thus, the ON state of the atomic switch is held stably. On the other hand, when the input V_{in} is at the high level (VH), the potential difference between the electrodes 102 and 103 of the atomic switch indicates $VH/2$. This value indicates the potential difference at which the atomic switch should be in the OFF state. Therefore, the OFF state is held stably. In other words, the NOT circuit according to the present embodiment operates with reliability and stability.

10 [0105] According to the present embodiment, the case where VH or VL is used as an input and $VH/2$ or VL is used as an output is described. In the NOT circuit shown in Fig. 14, according to the principle of operation of the atomic switch, under limitations that a potential difference between inputs (in the present embodiment, $VH - VL$) has to always be larger than a potential difference between outputs (in the present embodiment, $VH/2 - VL$), the potential difference between inputs and that between outputs can be freely set within the limitations.

15 [0106] In the third and fourth embodiments, a case where the potential difference between inputs is equivalent to that between outputs will be described in detail. In other words, a NOT circuit in which the level of an input is equivalent to the level of an output can be formed.

[0107] Fig. 16 is a schematic diagram of a NOT circuit according to a second embodiment of the present invention.

20 [0108] A NOT circuit comprising two-terminal devices with arrangement different from that shown in Fig. 14 will now be described as another embodiment.

[0109] The used components are exactly the same as those shown in Fig. 14 according to the ninth embodiment. In other words, a first electrode 112 serving as an electronic/ionic mixed conductor (Ag_2S) is formed on Ag 111 serving as a conductive substance. Mobile ions (Ag ions) 114 in the electronic/ionic mixed conductor are precipitated to form a bridge 115 comprising Ag atoms between the first electrode 112 and a second electrode (Pt) 113. An atomic switch with the above structure is used.

25 [0110] A voltage $VH/2$ corresponding to a high-level output is applied to the second electrode (Pt) 113 of the atomic switch through a resistor 116 (resistance R_3). An output terminal V_{out} is connected to the second electrode 113.

[0111] On the other hand, a voltage VL corresponding to a low-level output is applied to the conductive substance (Ag) 111 constituting the first electrode 112 of the atomic switch through a resistor 117 (resistance R_4). An input terminal V_{in} is connected to the first electrode 112 through a capacitor 118 (capacitance C_2).

30 [0112] It is assumed that $R(\text{ON})$ denotes a resistance of the atomic switch in the ON state and $R(\text{OFF})$ denotes a resistance of the atomic switch in the OFF state. According to the present embodiment, the resistors and the atomic switch, which satisfy the following relation, are used.

$$35 \quad R(\text{OFF}) \gg R_3 \gg R(\text{ON}) \sim R_4$$

[0113] The principle of operation of the NOT circuit shown in Fig. 16 will now be described in detail with reference to Fig. 17.

40 [0114] When the input V_{in} changes from a low level (VL) to a high level (VH) at time t_1 [refer to Fig. 17(a)], charges $Q = C_2 \times VH$ (C_2 denotes a capacitance of the capacitor) are accumulated in the capacitor 118. At this time, a potential V_{in}' of the first electrode 112 in the atomic switch changes due to a current, which temporarily flows, as shown in Fig. 17(b). In other words, the potential of the first electrode 112 in the atomic switch is temporarily remarkably higher than that of the second electrode 113, so that the atomic switch changes to the ON state (low resistance) [refer to Fig. 17(c)].

45 [0115] Thus, $R_3 \gg R(\text{ON})$. The output V_{out} indicates VL [refer to Fig. 17(d)]. Switching time t_s is almost determined by the capacitance C_2 of the capacitor 118 and the resistance R_4 of the resistor 117. For instance, when it is assumed that the capacitance C_2 of the capacitor is 1 pF and the resistance R_4 is 10 Ω , switching can be performed on the order of gigahertz.

50 [0116] On the other hand, when the input V_{in} changes from the high level (VH) to the low level (VL) at time t_2 [refer to Fig. 17(a)], the charges accumulated in the capacitor 118 are discharged. Due to a current which temporarily flows, the potential V_{in}' of the first electrode 112 in the atomic switch changes as shown in Fig. 17(b). In other words, the potential of the first electrode 112 in the atomic switch is temporarily remarkably lower than that of the second electrode 113, so that the atomic switch changes to the OFF state (high resistance) [refer to Fig. 17(c)]. Consequently, $R(\text{OFF}) \gg R_3$. The output V_{out} indicates $VH/2$ [refer to Fig. 17(d)].

55 [0117] Fig. 17(e) shows the potential difference between the electrodes 112 and 113 of the atomic switch. When the input V_{in} is at the low level (VL), the potential difference between the electrodes 112 and 113 of the atomic switch indicates $VH/2$. This value indicates a potential difference at which the atomic switch should be in the OFF state. Therefore,

the OFF state is held stably.

[0118] On the other hand, when the input V_{in} is at the high level (VH), the potential difference between the two electrodes 112 and 113 of the atomic switch indicates substantially zero. Thus, the ON state of the atomic switch is held stably. In other words, the NOT circuit according to the present embodiment operates with reliability and stability.

[0119] According to the embodiment, the case where VH and VL are used as inputs and VH/2 and VL are used as outputs is described. In the same case as the NOT circuit according to the ninth embodiment (Fig. 14), under limitations that a potential difference between inputs has to always be larger than a potential difference between outputs, the potential difference between inputs and that between outputs can be freely set within the limitations.

[0120] For the arrangement of the atomic switch, the resistors, and the capacitor, and the number of each device, the pattern other than that of the above-mentioned embodiment can be made. The principal characteristics of the present invention are to use the above devices as components.

[0121] Fig. 18 is a schematic diagram of a NOT circuit according to the third embodiment of the present invention. Fig. 19 includes graphs showing the principle of operation of the NOT circuit shown in Fig. 18.

[0122] The NOT circuit in which a potential difference between inputs is equivalent to that between outputs will now be described. A diode 109 is connected to a portion (V_{out}' in Fig. 18) corresponding to the output of the NOT circuit according to the ninth embodiment (Fig. 14). VH is applied to the other end of the diode 109 through a resistor 110 (resistance R5). An output terminal V_{out} is connected to the other end thereof. Further, the present NOT circuit differs from the NOT circuit according to the first embodiment (Fig. 14) with respect to a point that a voltage to be applied through the resistor 107 (resistance R2) is not VL, but VS.

[0123] The potential of V_{out}' is changed in the same way as the first embodiment except that the low level is not VL, but VS [refer to Fig. 19(b)]. According to the present embodiment, by satisfying the relation of $VH/2 < VF(VH - VS)$ (VF denotes a threshold voltage of the diode 109), the potential difference between inputs is equalized to that between outputs in the NOT circuit. In other words, when V_{out}' indicates VH/2, a voltage that is equal to or lower than the threshold voltage is applied to the diode 109. It is assumed that RB denotes a resistance of the diode 109 at this time and RF denotes a resistance thereof when a voltage that is equal to or higher than the threshold. The resistor 110 which satisfies the relation of $RB \gg R5 \gg RF$ is used. Fig. 19(c) shows a voltage to be applied to the diode. The resistances and a voltage to be applied are set so as to satisfy the following expressions.

$$R5/R2 = (VH - VL) / (VL - VF - VS)$$

$$VL > VF + VS$$

Thus, the output V_{out} is changed as shown in Fig. 19(d). In other words, the NOT circuit in which the potential difference between inputs is equivalent to that between outputs can be realized.

[0124] Fig. 20 is a schematic diagram of a NOT circuit according to a second embodiment of the present invention.

[0125] A NOT circuit in which a potential difference between inputs is equivalent to that between outputs can be formed on the basis of the NOT circuit according to the second embodiment shown in Fig. 16. A diode 119 is connected to a portion (V_{out}') corresponding to the output of the NOT circuit according to the tenth embodiment (Fig. 16). VH is applied to the other end of the diode 119 through a resistor 120 (resistance R6). An output terminal V_{out} is connected to the other end thereof. Further, the present NOT circuit differs from the NOT circuit according to the second embodiment with respect to a point that the voltage applied through the resistor 117 (resistance R4) is not VL, but VS.

[0126] The principle of operation is substantially the same as that of the NOT circuit described in the third embodiment. The resistor 120 which satisfies the relation of $RB \gg R6 \gg RF$ is used and the resistances and a voltage to be applied are set so as to satisfy the following expressions.

$$R6/2R4 = (VH - VL) / (VL - VF - VS)$$

$$VL > VF + VS$$

On this condition, the NOT circuit in which the potential difference between inputs is equivalent to that between outputs

can be realized. In the above case, the resistance of the atomic switch is substantially equivalent to R4. When the condition does not apply, it is necessary to control VS to some extent.

[0127] When the diode and the resistor are added to the NOT circuit in which the atomic switch, the resistors, and the capacitor are arranged according to various patterns, the above-mentioned NOT circuit in which the potential difference between inputs is equivalent to that between outputs can be constructed. In other words, the arrangement of the atomic switch, the resistors, the capacitor, and the diode is not limited to that described in the present embodiment. The present invention is characterized in that these devices are used as components.

[0128] Fig. 21 is a schematic diagram of a one-digit binary adder.

[0129] According to the present example, a case where the one-digit binary adder comprises a NOT circuit an AND circuit, and an OR circuit, the AND circuit and the OR circuit each having an atomic switch, will be described.

[0130] The NOT circuit according to the third embodiment shown in Fig. 18 is used. The AND circuit and the OR circuit, proposed by the inventors of the present application in Japanese Patent Application No. 2000-334686, are used. In the diagram, respective parts corresponding to the NOT circuit, the AND circuit, and the OR circuit are surrounded by dotted lines. In other words, the present one-digit binary adder comprises two NOT circuits 121 and 122, three AND circuits 123, 124, and 125, and one OR circuit 126.

[0131] Fig. 22 shows the circuits using logical symbols. In Fig. 22, reference numerals 121' and 122' denote the NOT circuits, 123', 124', and 125' denote the AND circuits, and 126' denotes the OR circuit.

[0132] For inputs X and Y, it is assumed that a high-level input indicates 1 and a low-level input indicates 0. Outputs S and C are as shown in Fig. 23. The one-digit binary adder, which is applied to a computer, can be constructed. This case is one example. According to the present invention, a NOT circuit can be constructed using two-terminal devices. Accordingly, all of logic circuits can be constructed using only the two-terminal devices.

[0133] As mentioned above embodiments of the present invention provide the following:

(A) A high-speed point contact array with low power consumption can be constructed, resulting in the realization of a multiple recording memory device, a logic circuit, and an arithmetic circuit.

(B) Since a NOT circuit can be constructed using two-terminal devices, all of logic circuits can be realized using only the two-terminal devices. A nanometer-sized atomic switch can be easily formed. Therefore, a nanometer-scale device can be realized.

Industrial Applicability

[0134] A point contact array, a NOT circuit, and an electronic circuit using the same are applicable to a logic circuit, an arithmetic circuit, and a memory device which are nano-scale.

Claims

1. A NOT circuit **characterised by** comprising a first electrode(102) made of a compound conductive material having ionic conductivity and electronic conductivity and a second electrode (103) made of a conductive substance and spaced apart from the first electrode (102), wherein conductance between the first and second electrodes (102,103) is controlled by forming a bridge (105) of metal atoms between the first and second electrodes (102, 103).
2. A NOT circuit according to Claim 1, wherein the compound conductive material is Ag₂S, Ag₂Se, Cu₂S, or Cu₂Se.
3. A NOT circuit according to Claim 1 or 2, comprising a resistor (106) and a capacitor (108), each of which serves as a two-terminal device.
4. A NOT circuit according to Claim 3, comprising a diode (119) in addition to the resistor (106) and the capacitor (108).
5. A NOT circuit according to Claim 3, wherein a voltage (V_{in}) to be applied to the first and second electrodes (102,103) is controlled through the capacitor (108) to control the conductance between the first and second electrodes.

Patentansprüche

1. NOT-Schaltkreis, **dadurch gekennzeichnet, daß** er eine erste Elektrode (102), die aus einem zusammengesetzten leitfähigen Material mit Ionenleitfähigkeit und Elektronenleitfähigkeit hergestellt ist, und eine zweite Elektrode (103) umfaßt, die aus einer leitfähigen Substanz hergestellt und von der ersten Elektrode (102) beabstandet ist, wobei

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der Leitwert zwischen der ersten Elektrode und der zweiten Elektrode (102, 103) durch Ausbilden einer Brücke (105) aus Metallatomen zwischen der ersten Elektrode und der zweiten Elektrode (102, 103) gesteuert wird.

- 5 2. NOT-Schaltkreis nach Anspruch 1, **dadurch gekennzeichnet, daß** das zusammengesetzte leitfähige Material Ag_2S , Ag_2Se , Cu_2S oder Cu_2Se ist.
3. NOT-Schaltkreis nach Anspruch 1 oder 2, umfassend einen Widerstand (106) und einen Kondensator (108), von denen jeder als ein Zweipol-Baustein dient.
- 10 4. NOT-Schaltkreis nach Anspruch 3, umfassend eine Diode (119) zusätzlich zum Widerstand (106) und zum Kondensator (108).
- 15 5. NOT-Schaltkreis nach Anspruch 3, **dadurch gekennzeichnet, daß** eine an die erste Elektrode und zweite Elektrode (102, 103) anzulegende Spannung (V_{in}) durch den Kondensator (108) gesteuert wird, um den Leitwert zwischen der ersten Elektrode und der zweiten Elektrode zu steuern.

Revendications

- 20 1. Un circuit NON **caractérisé en ce qu'il** comprend une première électrode (102) faite d'un matériau conducteur composite possédant une conductivité ionique et une conductivité électronique et une deuxième électrode (103) faite d'une substance conductrice et espacée de la première électrode (102), où la conductance entre la première et la deuxième électrodes (102, 103) est commandée par un pont (105) d'atomes métalliques entre la première et la deuxième électrodes (102, 103).
- 25 2. Un circuit NON selon la Revendication 1, où le matériau conducteur composite est Ag_2S , Ag_2Se , Cu_2S ou Cu_2Se .
3. Un circuit NON selon la Revendication 1 ou 2, comprenant une résistance (106) et un condensateur (108), chacun d'eux faisant office de dispositif à deux bornes.
- 30 4. Un circuit NON selon la Revendication 3, comprenant une diode (119) en plus de la résistance (106) et du condensateur (108).
- 35 5. Un circuit NON selon la Revendication 3, où une tension (V_{in}) à appliquer aux première et deuxième électrodes (102, 103) est commandée par l'intermédiaire du condensateur (108) afin de commander la conductance entre la première et la deuxième électrodes.

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FIG. 1

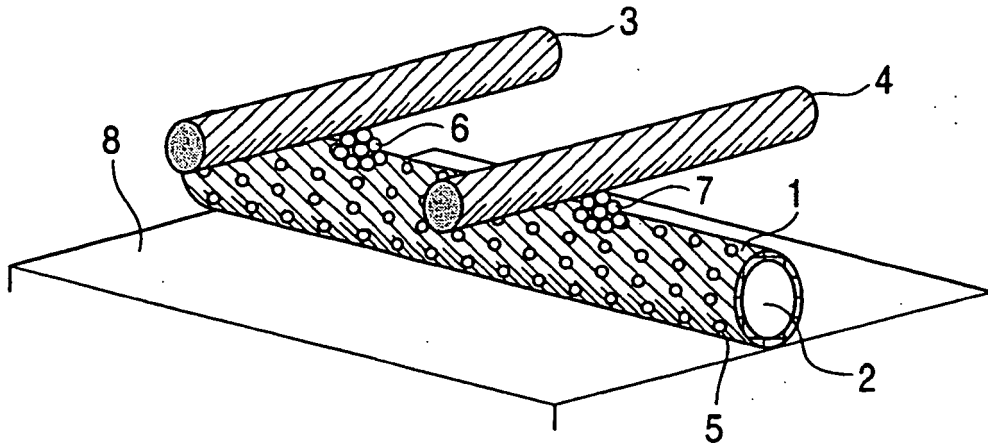


FIG. 2

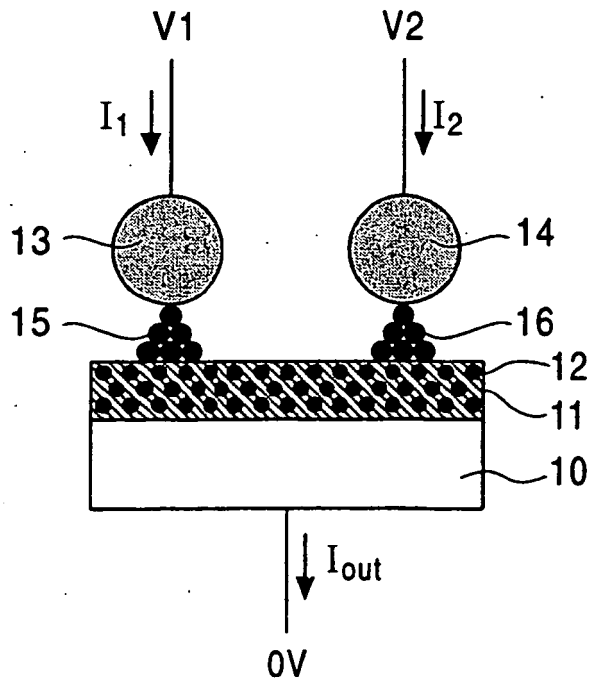


FIG. 3

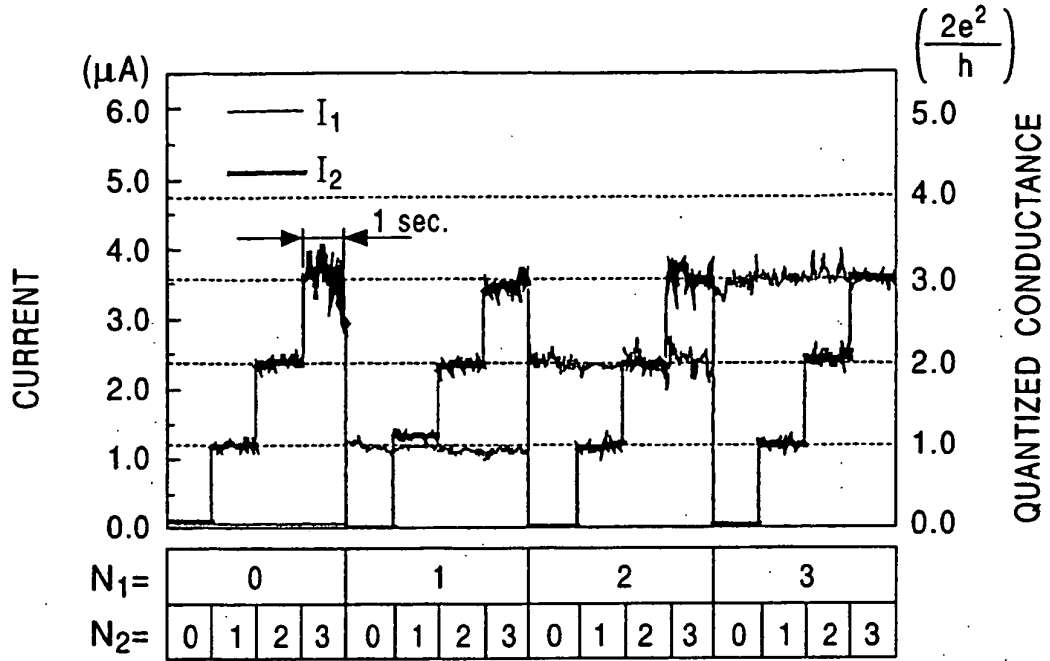


FIG. 4

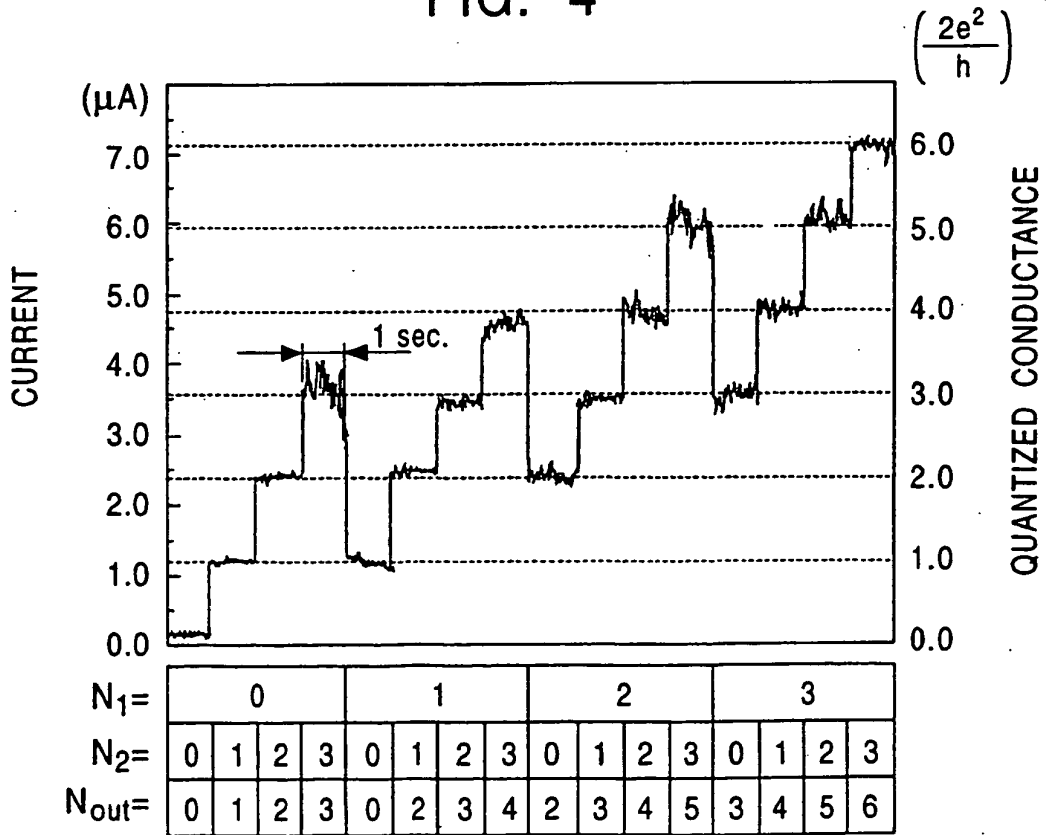


FIG. 5

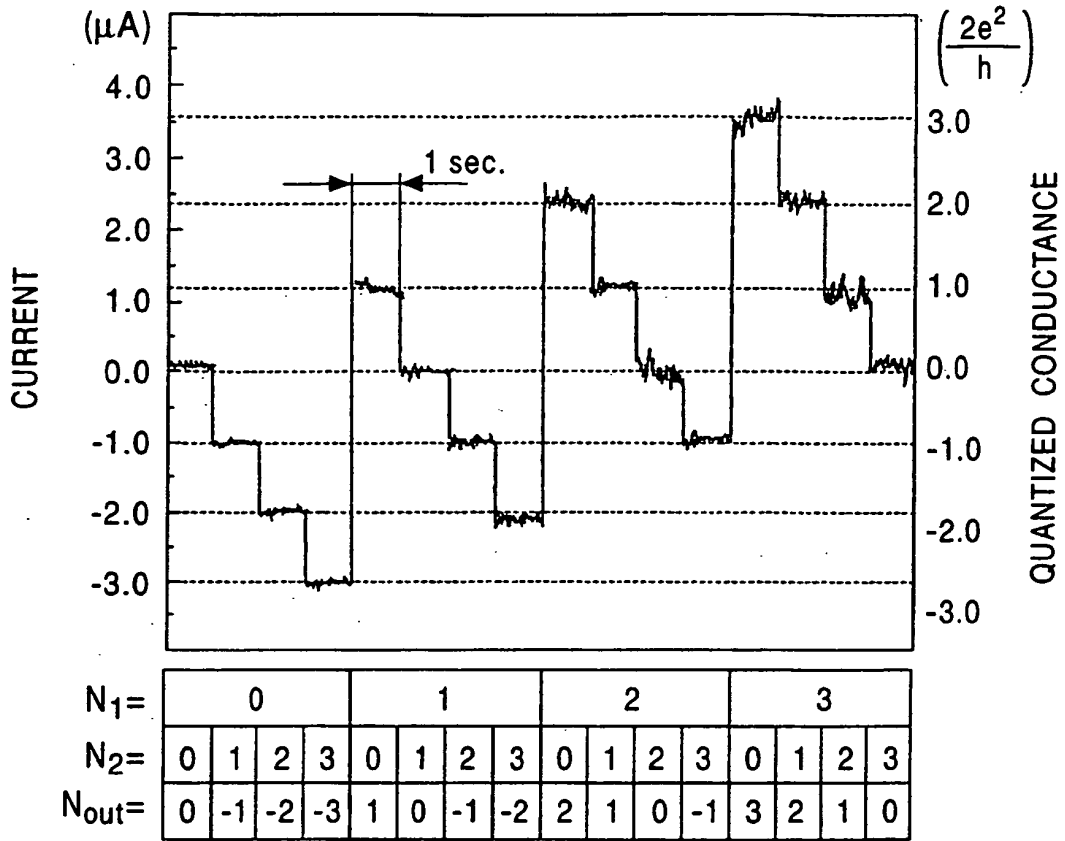


FIG. 6

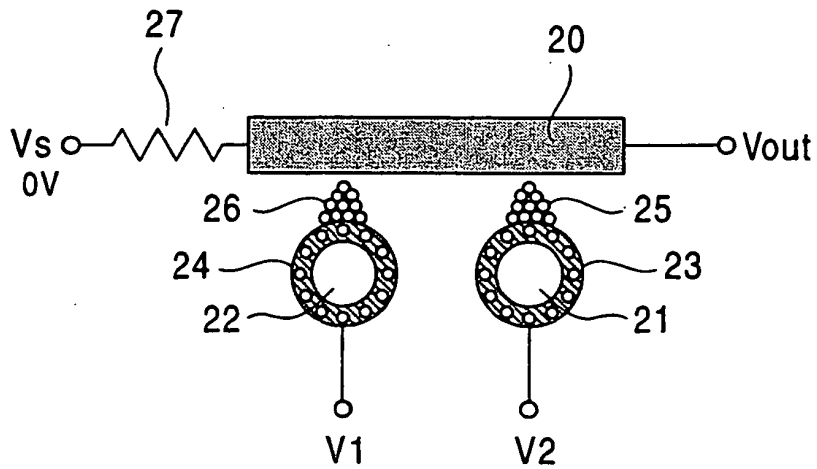


FIG. 7

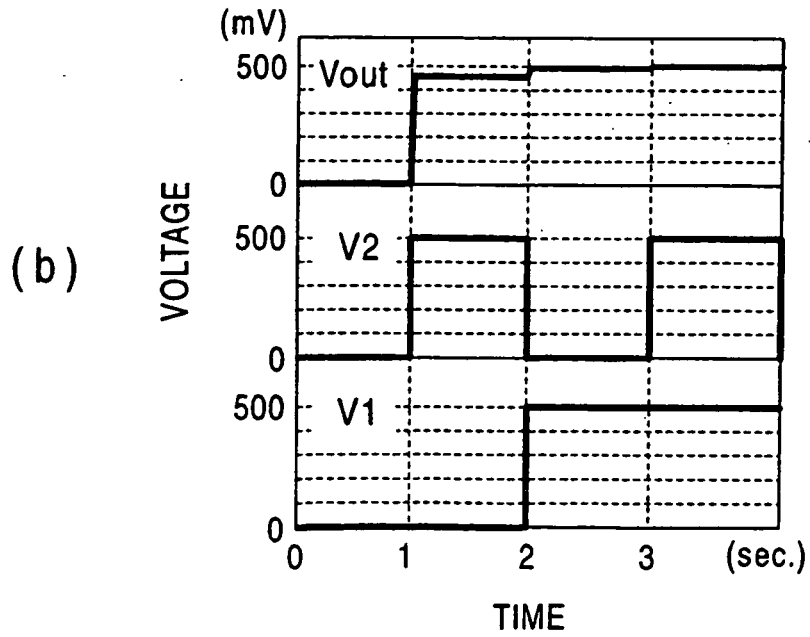
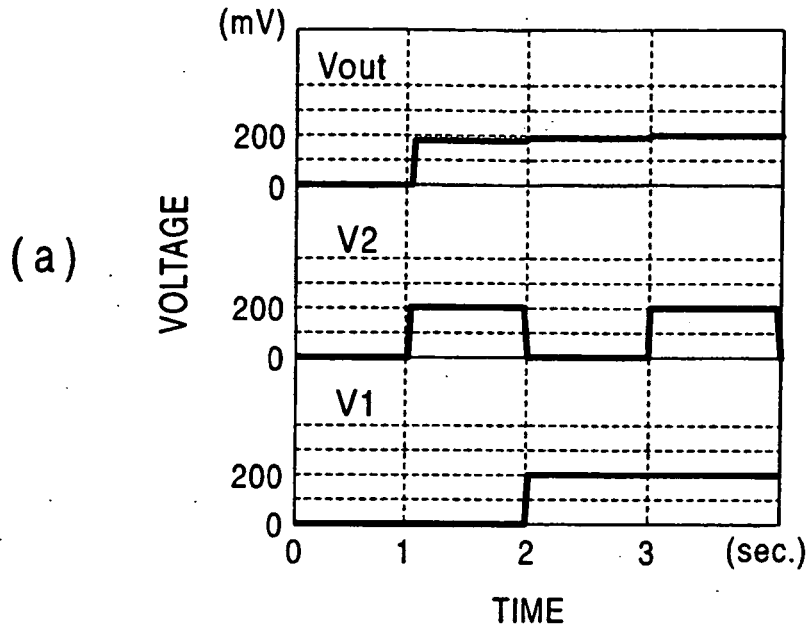


FIG. 8

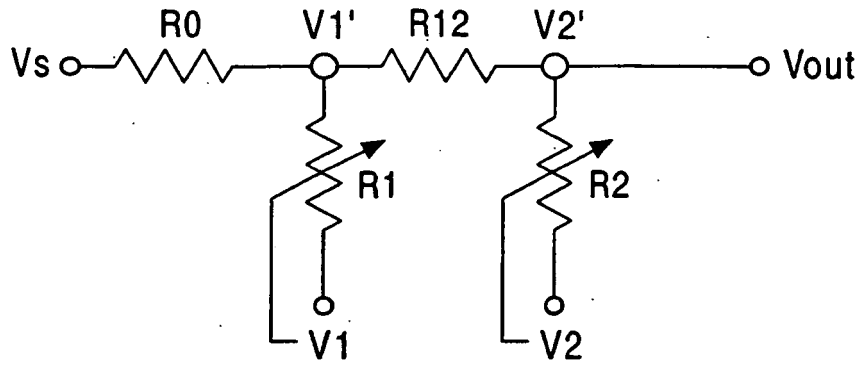


FIG. 9

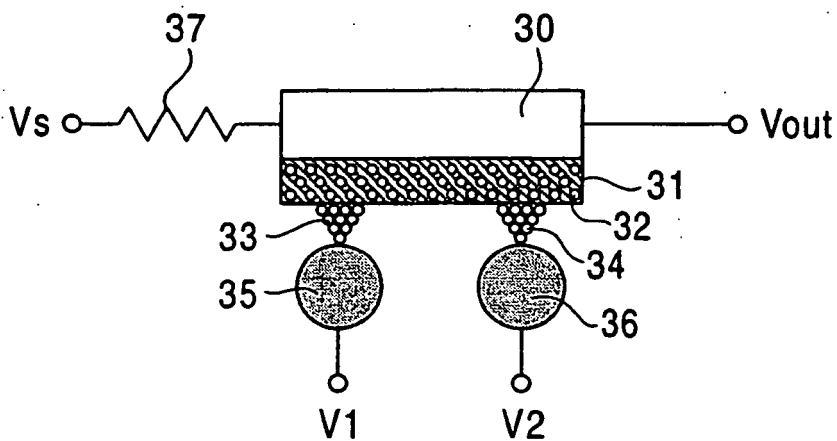


FIG. 10

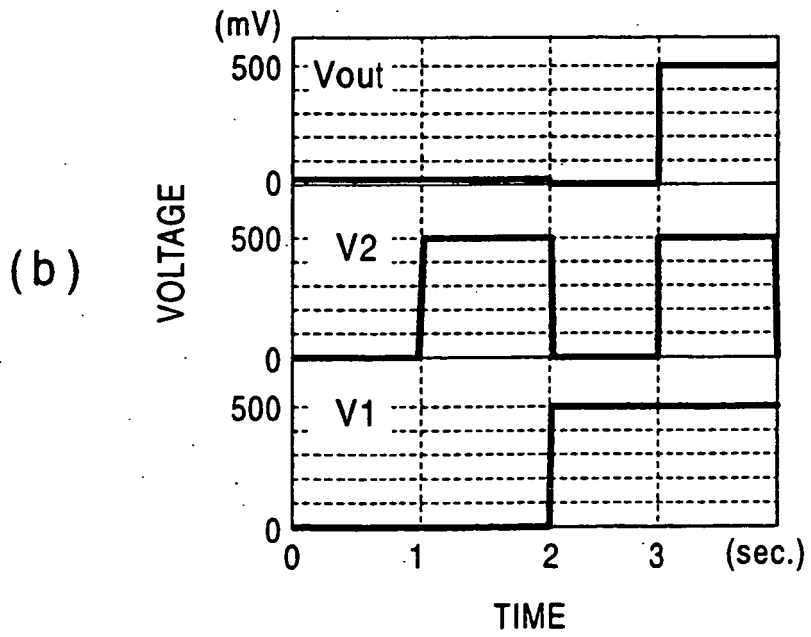
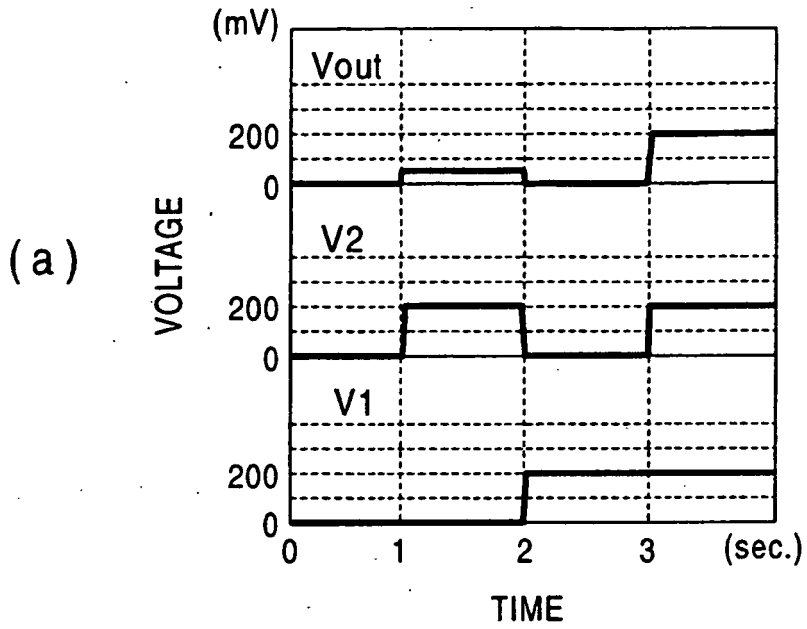


FIG. 11

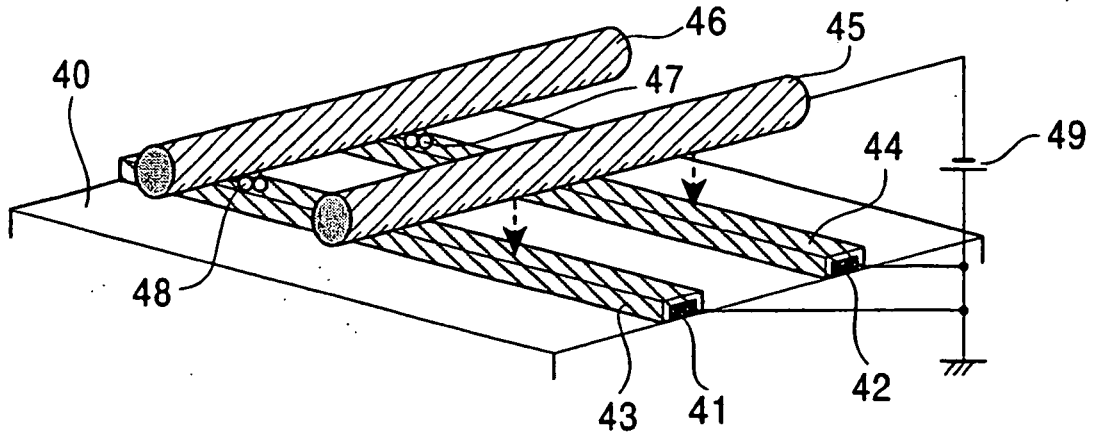


FIG. 12

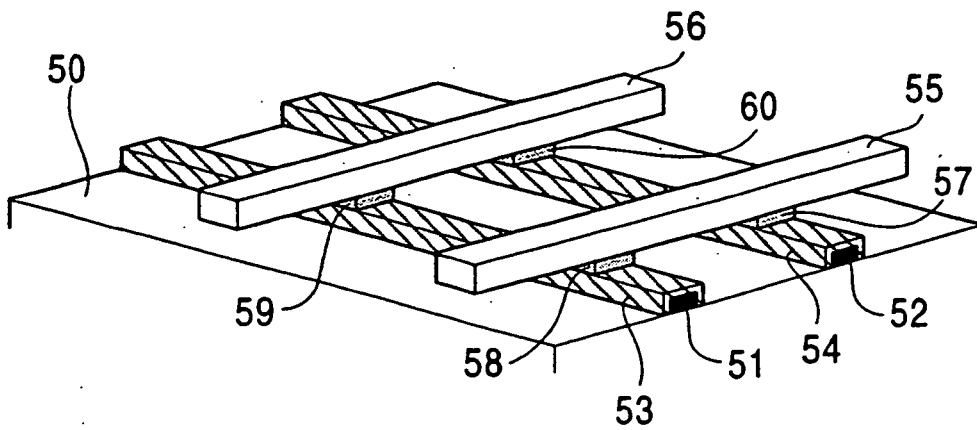


FIG. 13

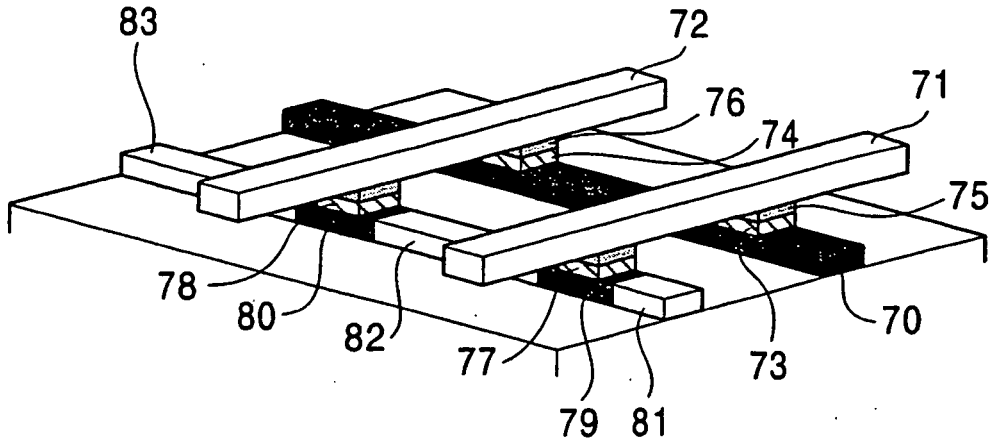


FIG. 14

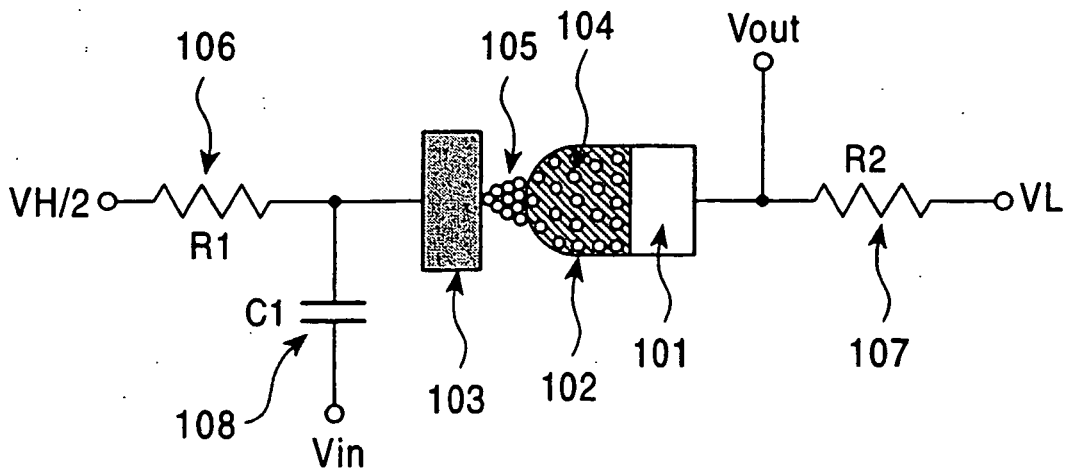


FIG. 15

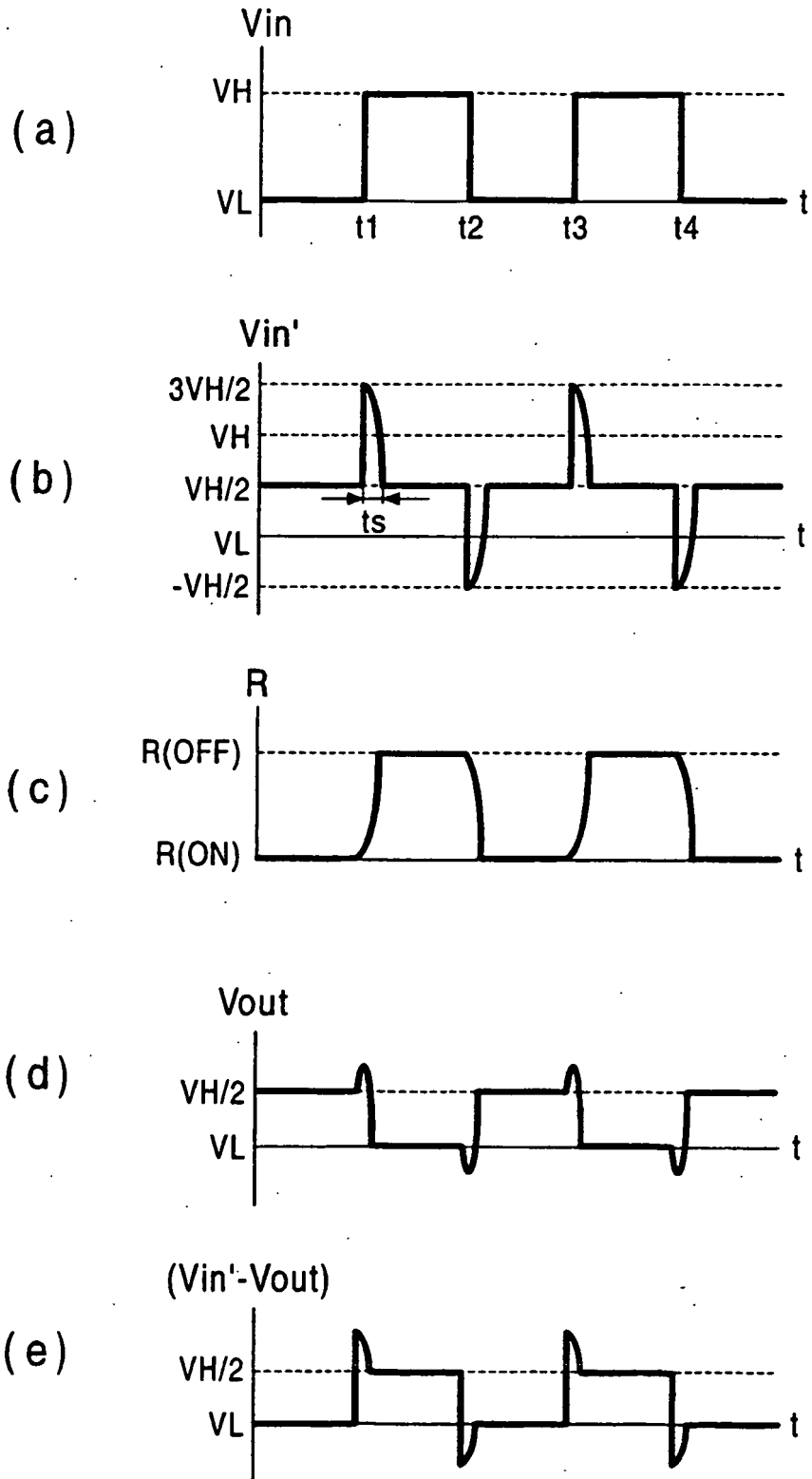


FIG. 16

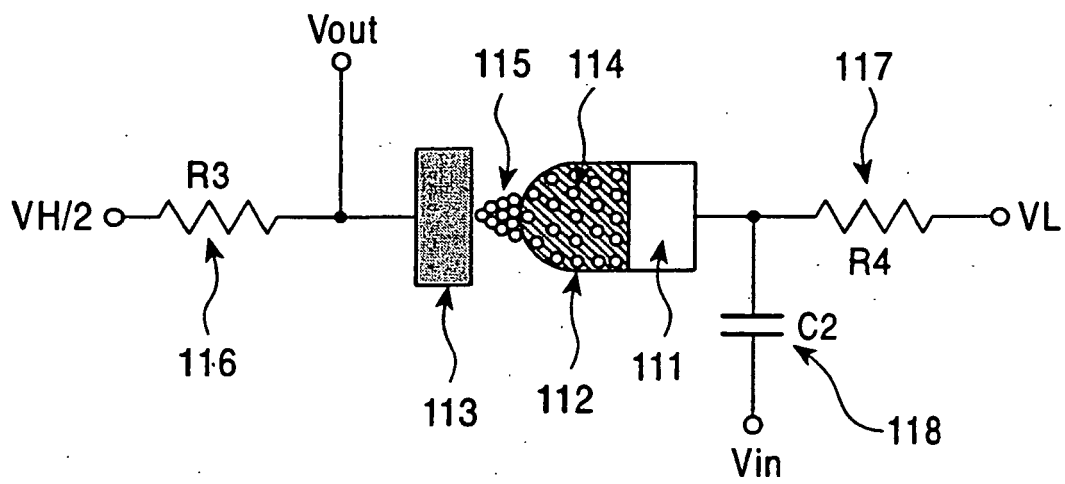


FIG. 17

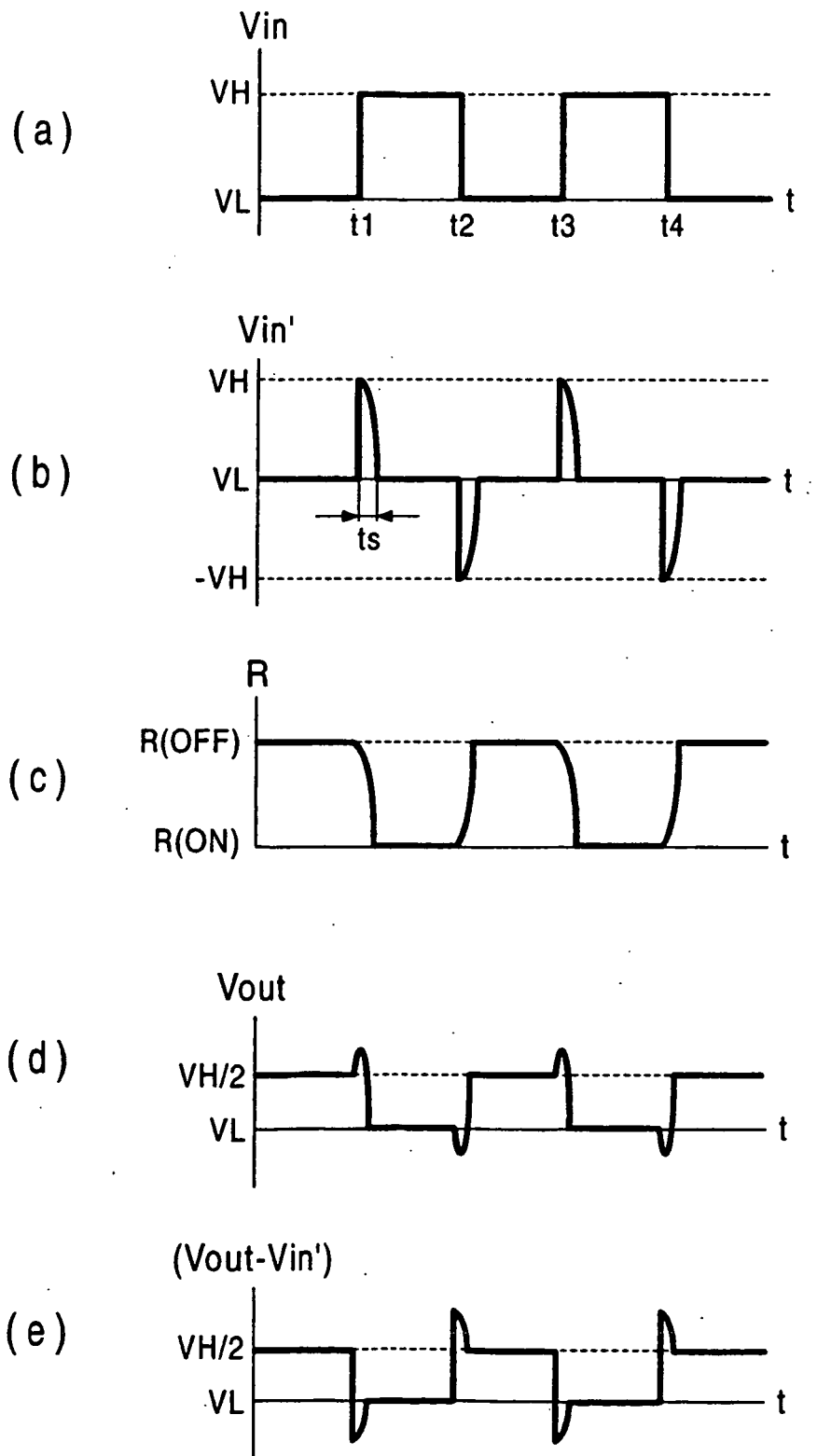


FIG. 18

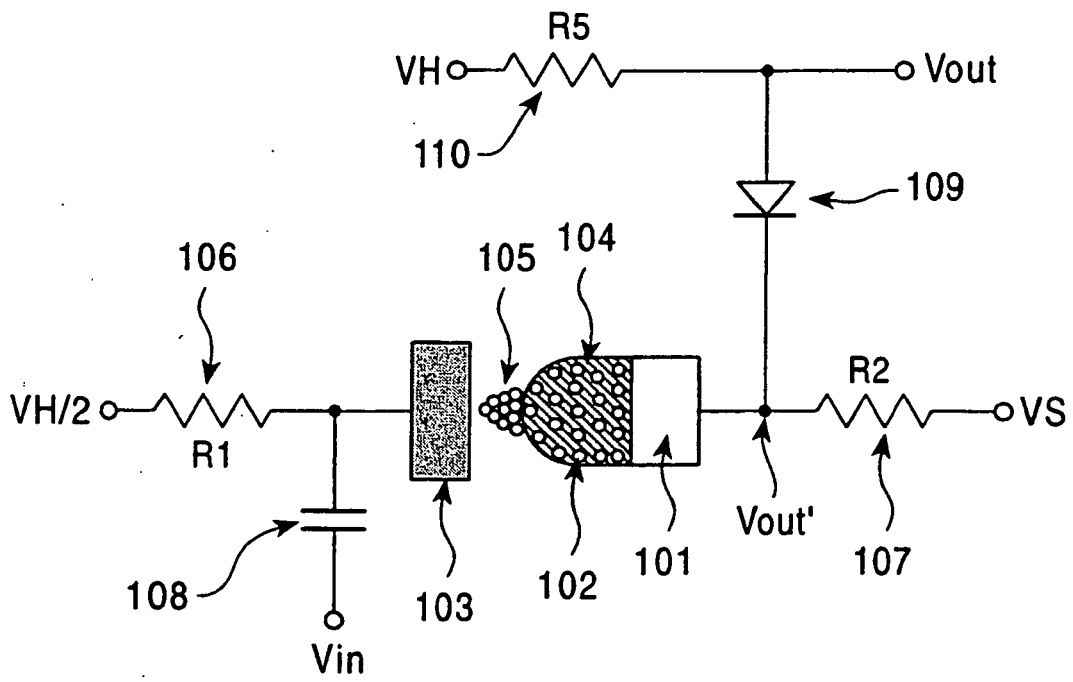


FIG. 19

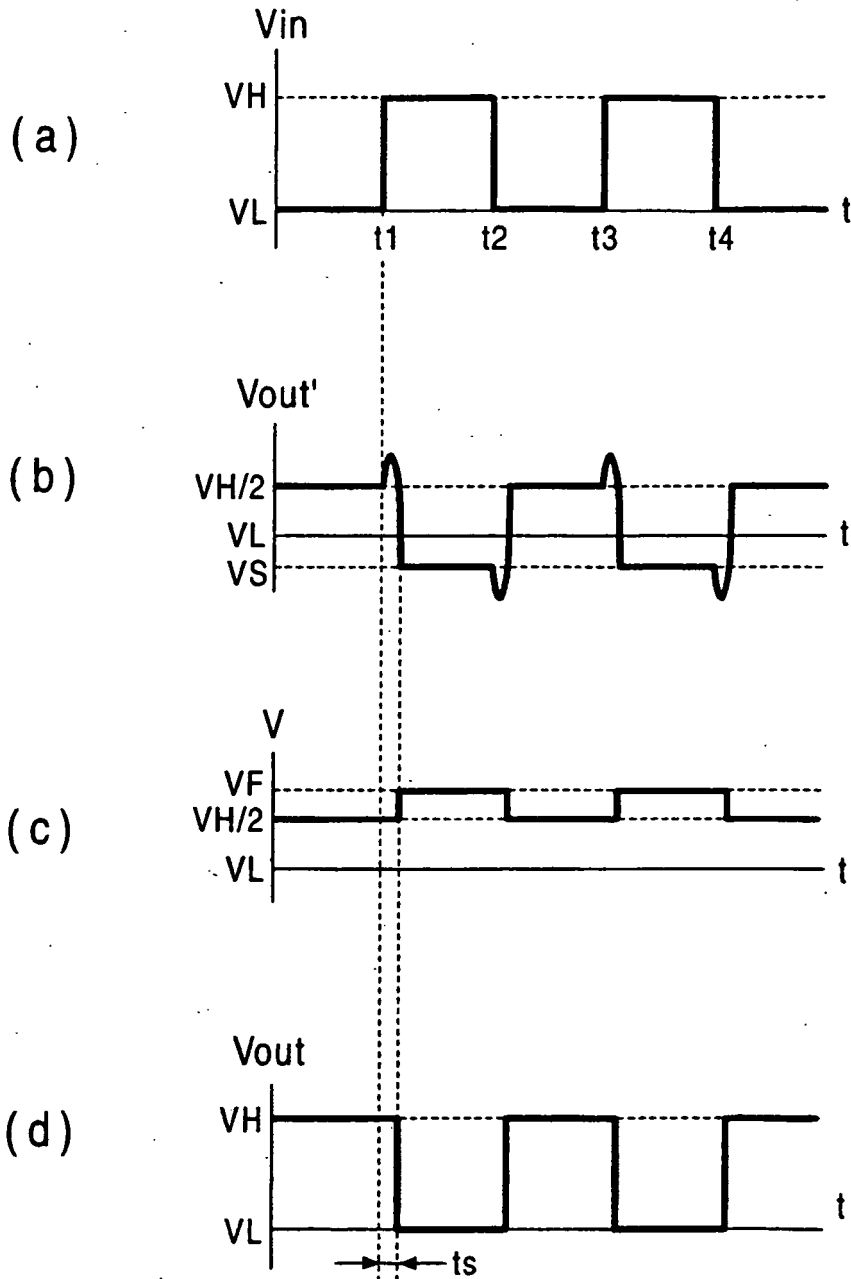


FIG. 20

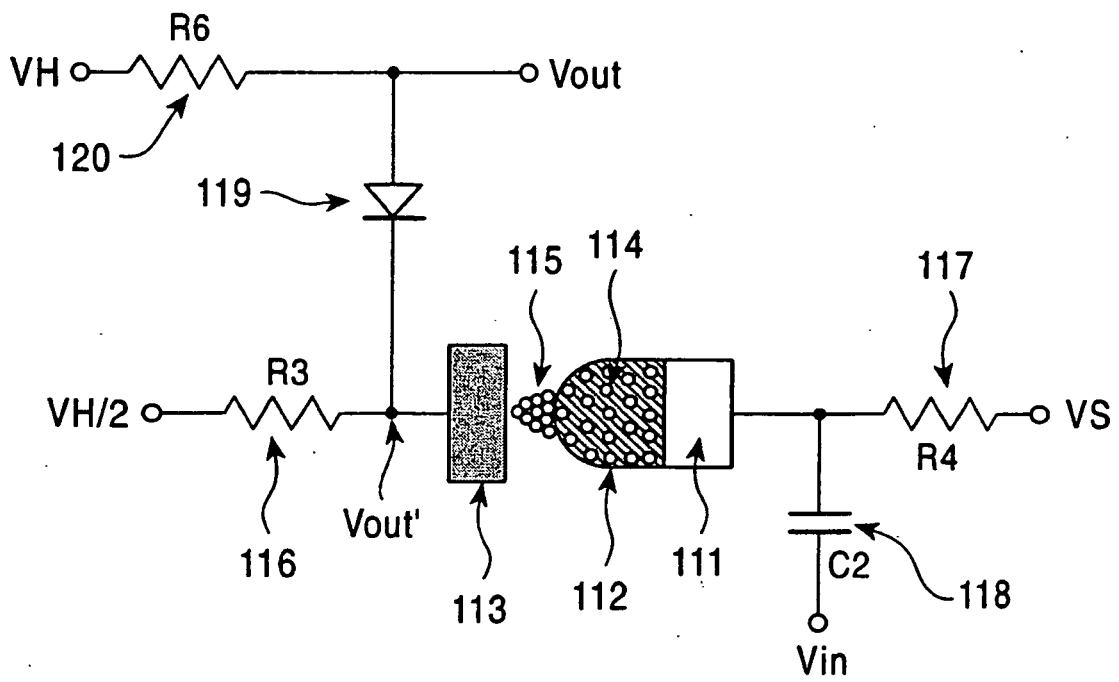


FIG. 21

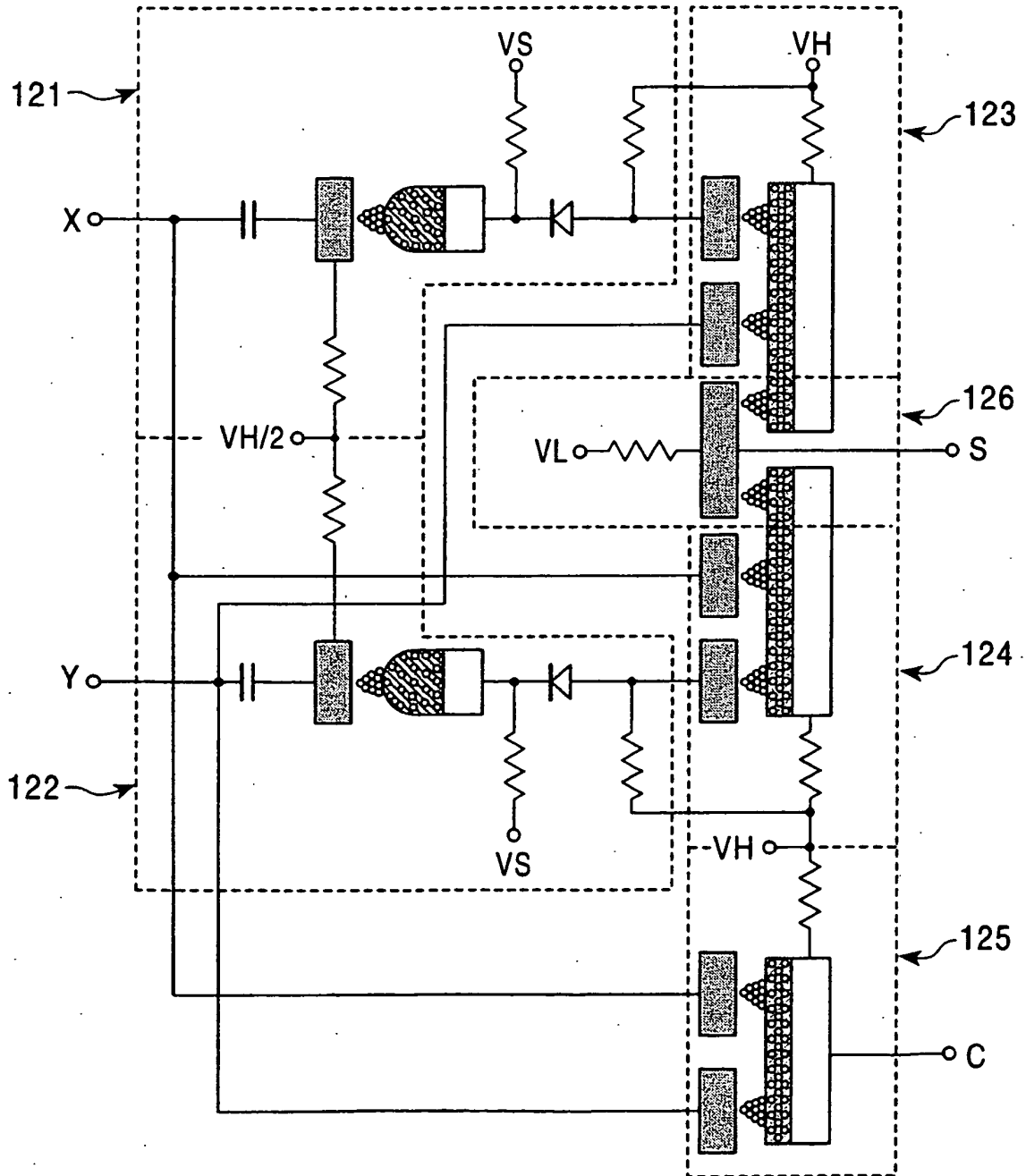


FIG. 22

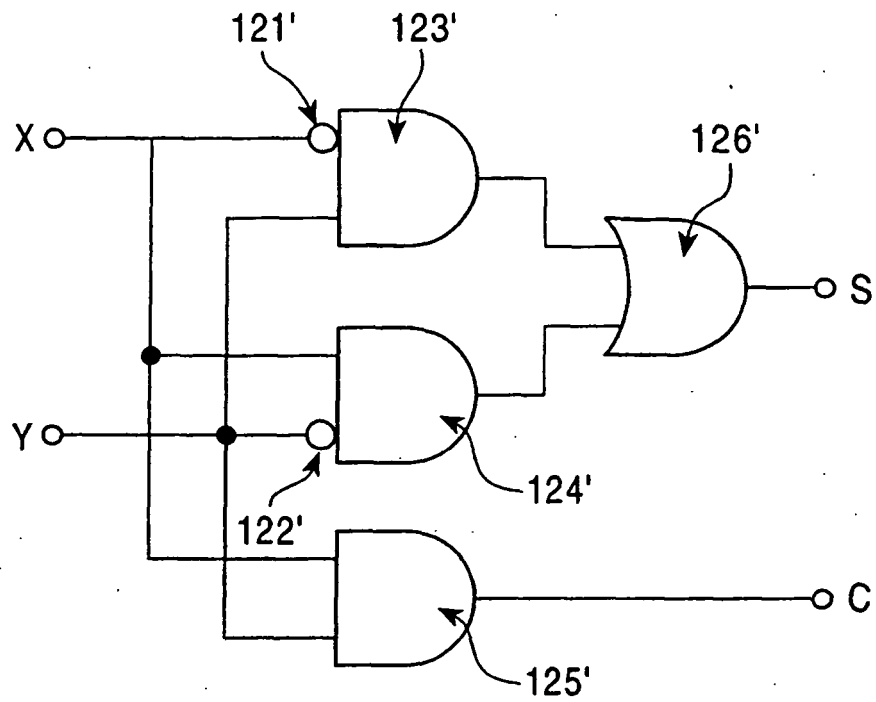


FIG. 23

X	Y	S	C
0	0	0	0
0	1	1	0
1	0	1	0
1	1	0	1

REFERENCES CITED IN THE DESCRIPTION

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