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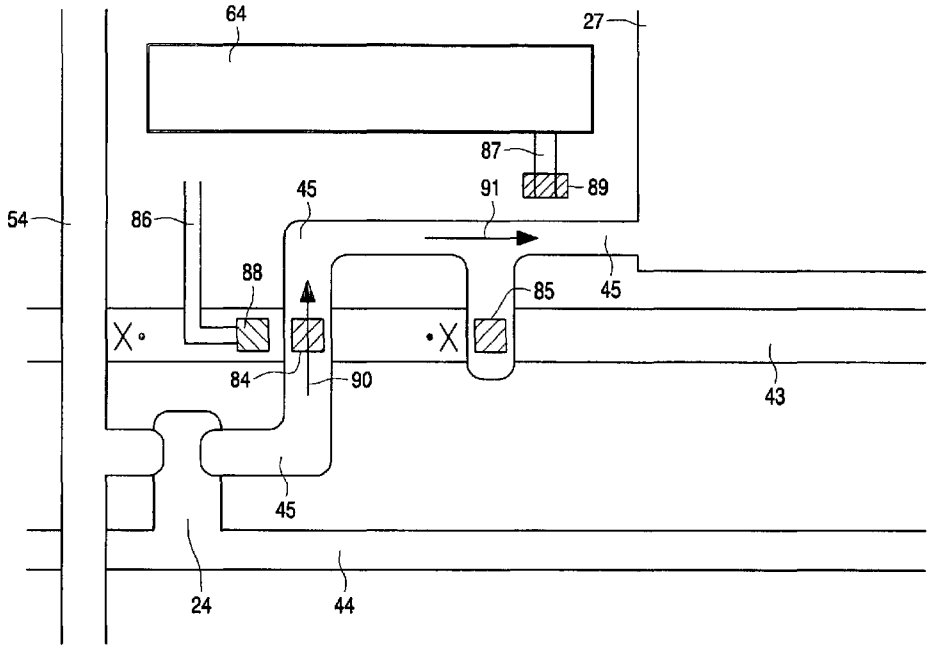

(57) Abstract: Magnetoresistive random access memory (MRAM) is used to provide in-pixel memory circuits for display devices. A memory circuit (25) comprises two MRAMs (60, 62), each coupled to a respective input of a flip-flop circuit (64). A display device (1) is provided comprising a plurality of pixels (20) each associated with a memory circuit (25). One of the MRAMs is a switchable MRAM (60), the other MRAM is a reference MRAM (62) arranged to provide a reference by which the changed states of the switchable MRAM (60) may be readily observed and measured in the form of a differential.

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MEMORIES AND MEMORY CIRCUITS

DESCRIPTION

The present invention relates to memories and memory circuits, particularly in-pixel memories and in-pixel memory circuits for display devices. The present invention also relates to methods of forming such memories and memory circuits. The present invention is particularly suited to, but not limited to, providing in-pixel memory circuits in active matrix liquid crystal display devices.

Known display devices include liquid crystal, plasma, polymer light emitting diode, organic light emitting diode, and field emission. Such devices comprise an array of pixels, usually in rows and columns. In active matrix display devices, each pixel is typically associated with one or more respective switching devices, such as thin film transistors, to provide an array of pixels and switching devices. In operation, the pixels are addressed according to an addressing scheme in which each pixel is regularly refreshed for each frame to be displayed with display data (e.g. video) specifying the intensity level the pixel is to display. Usually the addressing scheme selects the pixels on a row-by-row basis and provides individual intensity levels on a column-by-column basis.

One development in the field of display devices is to provide in-pixel memories, whereby a respective memory device is provided for each pixel, the memory devices being arranged in an array corresponding to the pixel array. Static images may then be displayed without a need to refresh, thereby saving power. This is potentially particularly attractive for display devices for portable devices such as mobile telephones, cordless telephones, personal digital assistants, and so on.

It is known to use static random access memory (SRAM) and dynamic random access memory (DRAM) circuits for such in-pixel memory.

Conventionally only one memory device (formed by a circuit) is provided for each pixel. A separate array of SRAM or DRAM circuits is provided in addition to the pixel and switching device array. This involves either a further entire manufacturing process in addition to that used for the pixel and switching device array, or the need for a large number of additional masking stages.

Quite separate from display device technology, one type of memory device is magnetoresistive random access memory (MRAM), in which a tunnel current depends on a magnetisation direction of two so-called magnetic electrodes. MRAM provides non-volatile memory. Use of such a memory (in applications unrelated to displays) is described for example in "Magnetoelectronic memories last and last...", Mark Johnson, IEEE Spectrum, February 2000, pages 33-40. As well as MRAMs based on tunnel barriers, other known types of MRAM include MRAMs based on giant magnetoresistance and MRAMs based on the Hall-effect.

One problem with the use of MRAM is that in operation MRAM provides, as its output, different resistance states (as opposed to e.g. a voltage change). Furthermore, the difference between the resistance states is low, usually less than 35%. Such factors may make absolute read-out difficult in the sense that any read-out circuit may need to be burdensomely precise in terms of absolute material characteristics and manufacturing tolerances.

The present invention uses MRAM technology to provide memory circuits, including memory circuits for in-pixel memory for display devices, in ways that alleviate the problems described above.

In a first aspect, the present invention provides a memory circuit comprising a switchable MRAM and a reference MRAM, arranged such that the varying state of the switchable MRAM is measurable by comparison with the constant state of the reference MRAM. The reference MRAM is preferably arranged to provide a reference by which the changed states of the switchable MRAM may be readily observed and measured in the form of a differential.

Preferably the MRAMs are coupled to a read-out circuit, preferably a flip-flop circuit.

Preferably a magnetic orientation of a pinned layer of the reference MRAM is substantially perpendicular to the possible orientation states of a free layer of the reference MRAM, such that both possible orientation states of the free layer of the reference MRAM provide substantially the same resistance through the MRAM.

Preferably the reference MRAM and the switchable MRAM are formed by common deposition processes and deposition layers, such that variations in the form or the behaviour of the switchable MRAM are, at least to an extent, followed by the reference MRAM.

The read-out circuit is preferably a flip-flop circuit. Preferably the flip-flop circuit comprises two inputs, and each of the MRAMs is coupled to a respective one of the flip-flop circuit inputs.

In a further aspect, the present invention provides a display device comprising a plurality of pixels and a plurality of memory circuits according to the first aspect, each pixel associated with or comprising a respective one or more of the memory circuits.

In a further aspect, the present invention provides a drive line arrangement for an in-pixel memory, wherein a drive line, for example a bit line, is arranged such that a current flowing along the bit line to an end-destination, for example a pixel electrode, passes over the switchable MRAM but not the reference MRAM. One preferred arrangement is for the bit line to cross over the switchable MRAM but merely be positioned over a reference MRAM.

In further aspects the present invention provides memory circuits or structures including a switchable MRAM and a reference MRAM for use in applications other than display applications, for example as sensors, preferably medical sensors.

Further aspects are as claimed in the appended claims.

Embodiments of the present invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a schematic illustration (not to scale) of a liquid crystal display device;

Figure 2 is a schematic illustration of a sample 2x2 portion of an array of pixels;

Figure 3 is a schematic illustration of a simple switchable MRAM stack;

Figure 4 is a circuit diagram of an in-pixel memory circuit;

Figure 5 shows further details of the overall pixel circuitry for a pixel;

Figure 6 shows a schematic diagram, not to scale, of a constructional layout employed for a pixel;

Figure 7 is a flowchart showing certain process steps used to form an in-pixel memory structure;

Figure 8 shows a cross-section between points X-X indicated in Figure 6;

Figure 9 shows a preferred switchable MRAM stack in cross-section (not to scale); and

Figure 10 shows the difference between a reference MRAM and a switchable MRAM 60.

Figure 1 is a schematic illustration (not to scale) of a liquid crystal display device 1, comprising two opposed glass plates 2, 4 (or any other suitable transparent plates). The glass plate 2 has an active matrix layer 6, which will be described in more detail below, on its inner surface, and a liquid crystal orientation layer 8 deposited over the active matrix layer 6. The opposing glass plate 4 has a common electrode 10 on its inner surface, and a liquid crystal orientation layer 12 deposited over the common electrode 10. A liquid crystal layer 14 is disposed between the orientation layers 8, 12 of the two glass plates. Except for any active matrix details described below, in

particular in relation to in-pixel memory, the structure and operation of the liquid crystal display device 1 is the same as the liquid crystal display device disclosed in US 5,130, 829, the contents of which are contained herein by reference.

Certain details of the active matrix layer 6, relevant to understanding this embodiment, are illustrated schematically in Figure 2 (not to scale). The active matrix layer 6 comprises an array of pixels. Usually such an array will contain many thousands of pixels, but for simplicity this embodiment will be described in terms of a sample 2x2 portion of the array of pixels 20-23 as shown in Figure 2.

In the field of display devices, there is often some variation in what is intended to be covered by the term "pixel". For convenience, in this example each pixel 20-23 is to be considered as comprising those elements of the active matrix layer 6 relating to that pixel in particular. The pixel 20 includes, inter-alia, a thin-film-transistor (TFT) 24, an in-pixel memory circuit 25, a drive circuit 26 and a pixel electrode 27. The TFT 24 and pixel electrode 27 are conventional, and may for example be as described in the earlier mentioned US 5,130, 829. The in-pixel memory circuit 25 and drive circuit 26 are not found in conventional liquid crystal devices, and will be described in more detail below.

The other pixels 21-23 comprise respective TFTs 28, 32, 36, in-pixel memory circuits 29, 33, 37, drive circuits 30, 34, 38 and pixel electrodes 31, 35, 39.

Also provided as part of the active matrix layer 6 is a plurality of addressing lines, as follows. Pixels 20 and 21 form a first row of the array of pixels, and pixels 22 and 23 form a second row of the array. The first row is provided with a polarity line 40, a refresh line 41, a read line 42, a word line 43 and a gate line 44 extending across the whole row. Also, a bit line 45 is provided for pixel 20, and a bit line 46 is provided for pixel 21. Likewise, the second row is provided with a polarity line 47, a refresh line 48, a read line 49, a word line 50 and a gate line 51 extending across the whole row, a bit line 52 for pixel 22, and a bit line 53 for pixel 23.

Pixels 20 and 22 form a first column of the array of pixels, and pixels 21 and 23 form a second column. The first column is provided with a column line 54. Likewise, the second column is provided with a column line 55.

By way of example, further details of the connections of the various pixel components and addressing lines, and operation of the pixels, will now be described for the case of pixel 20, but the following description applies in corresponding fashion to the other pixels 21-23.

The input to TFT 24 is connected to the column line 54, and the gate of the TFT is connected to the gate line 44, as in a conventional active matrix liquid crystal device. The output of the TFT 24 is connected to the bit line, which is connected to both the in-pixel memory circuit 25 and the pixel electrode 27. The word line 43 is connected to the in-pixel memory circuit 25. The read line 42 is connected to the in-pixel memory circuit. The polarity line 40 and the refresh line 41 are each connected to the drive circuit 26. The in-pixel memory circuit has two separate connections to the drive circuit 26. The drive circuit 26 is connected to the pixel electrode.

In operation, as with conventional active matrix display devices, row selection is performed via the gate line 44 and intensity level data is provided via the column line 54. The output of the TFT 24, i.e. in effect the intensity level data, is delivered to the pixel electrode via the bit line 45. This in itself corresponds to conventional operation of an active matrix display device. However, here, additionally the output from the TFT 24 is also delivered by the bit line 45 to the in-pixel memory circuit, and driving of the pixel electrode 27 by the drive circuit 26 is controlled by the resulting memory setting of the in-pixel memory circuit 25, as will be described in more detail below. The drive circuit 26 and the in-pixel memory circuit 25 are further controlled by inputs provided via the polarity line 40, the refresh line 41 and the read line 42, as will also be described in more detail below.

Before describing the above mentioned features in further detail, it will be helpful to provide an outline summary of the operation of a MRAM structure. Figure 3 shows a schematic illustration of a simple switchable MRAM stack. The MRAM stack comprises two ferromagnetic layers, namely a

free layer 102 and a pinned layer 106, each made for example of $Ni_{81}Fe_{19}$ and having a thickness of several nanometres, separated by an insulation layer 104, being for example 1 to 2 nm thick and made for example from Al_2O_3. The free layer 102 and the pinned layer 106 are each often referred to as magnetic electrodes. The insulation layer 104 serves as a tunnel barrier layer. An electrical contact is made with the free layer 102 and with the pinned layer 106. In this example, these are the bit line 45 and a contact 108 (in the pixel array embodiment shown in Figure 2, such a contact of each MRAM is connected to the flip-flop circuit 64 via a respective flip-flop connection as will be described in more detail below). A further electrical supply line is provided below the MRAM stack but insulated therefrom. This further electrical supply line runs orthogonal to the bit line 45, i.e. in and out of the page in Figure 3. In this example, this further electrical supply line is the word line 43.

The switchable MRAM stack operates as follows. The pinned layer 106 has a fixed magnetisation orientation shown by arrow 110. The free layer is capable of being switched between two magnetic orientations, as indicated by double-headed arrow 112. A write current 114, 116 is applied to the bit line 45 and the word line 43 to control or set the magnetic orientation 112 of the free layer. This may be set either parallel to or anti-parallel to the magnetic orientation 110 of the pinned layer 106. These two possibilities are each stable when set if no further write current 114, 116 is applied.

These two states are distinguishable, i.e. capable of being read-out, as follows. A read-out current 118, 120, 122 may be passed through the MRAM stack from the bit line 45 to the contact 108 due to tunnelling of electrons through the tunnel barrier layer 104. The resistance encountered by this current depends upon the tunnelling resistance of the tunnel barrier layer 104, which itself directly depends upon whether the magnetic orientation 112 of the free layer 102 is parallel to or anti-parallel to the magnetic orientation 110 of the pinned layer 106. The maximum resistance variation of present MRAM stacks is however typically only about 35%.

Further details of the MRAM stacks employed in the present embodiment will be described later below, but these outline details should

assist in understanding details of the pixel array being described, in particular the function of the word line 43 which passes under the MRAM stacks but does not directly connect to them, and the bit line 45 and contact 108 (connected in this embodiment to the flip-flop circuit 64) which are in direct contact with respective ends of the MRAM stack.

Figure 4 is a circuit diagram of the in-pixel memory circuit 25. The in-pixel memory circuit 25 comprises two MRAMs, namely a first MRAM 60 and a second MRAM 62, and a flip-flop circuit 64. The MRAMs 60, 62 serve as memory elements, and the flip-flop circuit 64 serves as a read-out circuit for reading out the memory state of the memory elements.

The first MRAM 60 is a switchable MRAM as described above with reference to Figure 3. The second MRAM 62, however, is a reference MRAM that does not switch. Figure 10 shows the difference between the reference MRAM 62 and the switchable MRAM 60.

Referring to Figure 10, a simplified illustration of the first MRAM 60 is shown, highlighting the above described free layer 102, insulation layer 104 serving as a tunnel barrier layer, and pinned layer 106. The pinned layer 106 has a fixed magnetisation orientation shown by arrow 110. The free layer 102 is switchable between two magnetic orientations as indicated by double-headed arrow 112. As described above, in the first MRAM 60, the two switchable directions of the magnetic orientation 112 of the free layer are respectively substantially parallel to or anti-parallel to the magnetic orientation 110 of the pinned layer, providing two distinguishable states. The second MRAM 62 includes three layers corresponding to those described here for the first MRAM 60, i.e. a free layer 102a, an insulation layer 104a serving as a tunnel barrier layer, and a pinned layer 106a. The pinned layer 106a has a fixed magnetisation orientation, shown by arrow 110a, which is the same as the fixed magnetisation orientation 110 of the pinned layer 106 of the first MRAM 60. The free layer 102a is switchable between two magnetic orientations as indicated by double-headed arrow 112a. In the case of the second MRAM 62, these two switchable directions of the magnetic orientation 112a of the free layer 102a are both substantially perpendicular to the

magnetic orientation 110a of the pinned layer 106a, thus no difference is made to the resistance of the second MRAM 62 when the magnetic orientation 112 of the free layer is switched between its two possible directions. Thus in effect, as viewed by a read-out circuit, no switching has in effect taken place, and the second MRAM 62 serves as and may be considered as a reference MRAM. For clarity, a view 201 looking down the second MRAM stack from above is shown of the magnetic orientation 110a of the pinned layer substantially perpendicular to the two magnetic orientations of the free layer as indicated by double-headed arrow 112a.

In this example, the perpendicular arrangement of the second MRAM 62 rather than the parallel arrangement of the first MRAM 60 is achieved by forming the two MRAMs from the same material layers during a common deposition process, but the width and depth of the MRAM stack providing the second MRAM 62 is made different to that of the MRAM stack providing the first MRAM 60. However, in other examples, the different magnetic orientations may be provided using any other suitable process.

In the above described arrangement, the magnetic orientation 110a of the pinned layer 106a of the second MRAM 62 is the same direction as the magnetic orientation 110 of the pinned layer 106 of the first MRAM 60, as this is most convenient for forming them from the same deposition layers. However, if for any reason it is desired to have the magnetic orientation 110a of the pinned layer 106a of the second MRAM 62 substantially perpendicular to that of the first MRAM 60 (with the free layer orientations the same instead) then this can be implemented, for example, using techniques for realising different exchange bias directions on a same substrate as disclosed in WO 0079298, which is incorporated herein by reference.

Also, in the above described arrangement, the two magnetic orientations 112a of the free layer 102a of the second MRAM 62 are switchable, but as described make no difference to the tunnelling resistance of the second MRAM 62. Hence the second MRAM 62 serves as a reference MRAM. Another possibility is for the second MRAM 62 to comprise a free layer with any form of magnetisation orientation states, including non-switchable

ones, provided they are substantially perpendicular to the magnetisation orientation 110a of the pinned layer 106a.

Referring again to Figure 4, the flip-flop circuit 64 comprises two p-type transistors, implemented as TFTs and hereinafter referred to as a first p-type TFT 66 and a second p-type TFT 67; and two n-type transistors, implemented as TFTs and hereinafter referred to as a first n-type TFT 68 and a second n-type TFT 69. The TFTs are arranged to provide in effect two input chains, a first input chain, in this example comprising the first p-type TFT 66 and first n-type TFT 68, connected to the first MRAM 60, and a second input chain, in this example comprising the second p-type TFT 67 and the second n-type TFT 69, connected to the second MRAM 62. The remaining end of each of the input chains of the flip-flop circuit 64 is connected to the read line 42. The respective other ends of the first MRAM 60 and the second MRAM 62 are connected to the bit line 45. (Operation of the MRAMs also involves the word line 43, as will be described later below, but for clarity this is not shown in Figure 4.) The flip-flop circuit comprises two output connections, hereinafter referred to as a first output connection 70 and a second output connection 71, which provide the two (complementary) flip-flop circuit outputs, represented, as is conventional, as D and $\overline{D}$ in Figure 4.

In this example the detailed connections of the flip-flop circuit 64 components are as follows. Each TFT 66-69 comprises, in conventional fashion, one gate and two source/drain terminals (hereinafter referred to as a first and a second terminal). In operation, one of the source/drain terminals functions as the source of the TFT and the other of the source /drain terminals functions as the drain of the TFT. The question of which source/drain terminals serves as the source and which serves as the drain at any particular moment is determined by the polarity of the applied voltage at that moment.

The first terminal of the p-type TFT 66 and the first terminal of the second p-type TFT 67 are connected to each other and to the read line 42. The gate of the first p-type TFT 66, the gate of the first n-type TFT 68, the second terminal of the first p-type TFT and the first terminal of the second n-type TFT 69 are connected to each other and to the first output connection 70.

The second terminal of the first p-type TFT 66, the first terminal of the first n-type TFT 68, the gate of the second p-type TFT 67 and the gate of the second n-type TFT 69 are connected to each other and to the second output connection 71. The second terminal of the first n-type TFT 68 is connected to the first MRAM 60. The second terminal of the second n-type TFT 69 is connected to the second MRAM 62.

In operation, the first MRAM 60 is set at a particular resistance state using the bit line 45 and word line 43, and this state and the constant state of the second MRAM 62 are read-out by the flip-flop circuit 64 operating as follows. Initially the bit line 45 and the read line 42 are at the same potential, for example 0V. The voltages on the two nodes of the flip-flop, 70 and 71, will be substantially the same. In order to read the state of the MRAMs the read line is made positive with respect to the bit line, for example by switching it from 0V to 3V, thus applying a power supply voltage to the flip flop circuit. The voltages on both nodes of the flip flop circuit will initially start to charge towards the mean value of the voltages on the bit and read lines, 1.5V. The rate of change of the voltages on the nodes will depend on the resistance of the MRAM elements, the resistance of the TFTs and the capacitance of the nodes of the circuit. One of the MRAM elements will have a lower resistance than the second. For example the resistance of MRAM element 60 may be lower than MRAM element 62. In this case the voltage on the flip flop node 70 will become more positive than that on node 71. This voltage difference is then amplified by the positive feedback within the flip flop circuit so that node 70 settles at the potential on the read line, 3V, and node 71 settles at the voltage on the bit line, 0V.

Figure 5 shows further details of the overall pixel circuitry for the pixel 20. In addition to those items already described above (and indicated by the same reference numerals as used above), Figure 5 shows further details of the drive circuit 26, and its connection, along with that of the bit line 45, to the pixel electrode 27. This connection to the pixel electrode 27 is shown in circuit terms, as is conventional, as connection to a storage capacitor 80 of capacitance C_s and a capacitance C_{LC} of the liquid crystal cell formed by the

liquid crystal layer 14 between the pixel electrode 27 and the opposing common electrode 10.

The drive circuit 26 comprises, in this example, four transistors, implemented as TFTs and hereinafter referred to as a first drive circuit TFT 75, a second drive circuit TFT 76, a third drive circuit TFT 77 and a fourth drive circuit TFT 78. The second drive circuit TFT 76 is a p-type TFT; the other three drive circuit TFTs 75, 77, 78 are n-type TFTs. The drive circuit TFTs 75-78 are arranged to provide a single drive input to the pixel electrode 27 based on the two outputs D and $\bar{D}$ from the flip-flop circuit 64.

In this example the detailed connections of the drive circuit TFTs 75-78 are as follows. The gates of the first drive circuit TFT 75 and the third drive circuit TFT 77 are connected to each other and to the refresh line 41. The gates of the second drive circuit TFT 76 and the fourth drive circuit TFT 78 are connected to each other and to the polarity line 40. The first terminal of the first drive circuit TFT 75 is connected to the first flip-flop output connection 70. The first terminal of the third drive circuit TFT 77 is connected to the second flip-flop output connection 71. The second terminal 75 of the first drive circuit TFT 75 is connected to the first terminal of the second drive circuit TFT 76. The second terminal of the third drive circuit TFT 77 is connected to the first terminal of the fourth drive circuit TFT 78. The second terminal of the second drive circuit TFT 76 and the second terminal of the fourth drive circuit TFT 78 are connected to each other and to the pixel electrode 27, i.e. to the storage capacitor 80 and the liquid crystal capacitance 82.

In operation, signals are applied to the polarity line 40, the refresh line 41, the read line 42, the word line 43, the gate line 44 and the column line 54 as follows, and consequently the drive circuit operates as follows to provide the required input to the pixel electrode 27, i.e. to the storage capacitor 80 and the liquid crystal capacitance 82. One way in which the circuits of Figure 5 may be operated in order to provide appropriate drive signals for the liquid crystal capacitance is as follows. The liquid crystal normally requires a drive voltage waveform which alternates in polarity with respect to the common electrode of the display. This is achieved by driving the pixel with positive and negative

drive signals in successive pixel refresh periods. In order to refresh the pixel electrode with a positive drive signal the data must first be read from the MRAMs. Initially the word line and the read line are at the same potential, for example 0V. The read line is then switched to a positive voltage level, for example 3V, and the flip-flop circuit 64 takes on a state determined by the state of the first MRAM 60. If MRAM 60 has a higher resistance than MRAM 62 then node 70 will settle at a voltage level of 0V and node 71 will settle at a voltage of 3V. The pixel is refreshed by taking the signal on the refresh line from a low voltage level to a high voltage level. This turns on the two transistors 75 and 77 allowing the data voltages generated by the flip flop circuit to be passed to the liquid crystal capacitance. During the positive refresh period the polarity line is held at a high voltage level. This turns on transistor 78 so that the liquid crystal capacitance becomes charged to the voltage present on node 71 which in this example is 3V. After the liquid crystal capacitance has been charged the refresh line is returned to a low voltage level, turning off transistors 75 and 77 and the voltage on the read line is returned to 0V.

In order to refresh the pixel electrode with a negative drive signal the data must again be read from the MRAMs but in this case this is achieved by taking the word line to a negative voltage level, for example -3V. If the first MRAM 60 has a higher resistance than the second MRAM 62 then node 70 will settle at a voltage level of -3V and node 71 will settle at a voltage of 0V. The pixel is refreshed by once again taking the signal on the refresh line from a low voltage level to a high voltage level. During the negative refresh period the polarity line is held at a low voltage level. This turns on transistor 76 so that the liquid crystal capacitance becomes charged to the voltage present on node 70 which in this example is -3V. After the liquid crystal capacitance has been charged the refresh line is returned to a low voltage level, turning off transistors 75 and 77 and the voltage on the read line is again returned to 0V.

In the case where the resistance of the first MRAM 60 is higher than that of the second MRAM 62 the liquid crystal capacitance is driven with a voltage waveform having an amplitude of 6V. In the case where a normally

white transmissive TN LC effect is being employed this would cause the pixel to be dark. If the relative resistance of the MRAMs is reversed so that the first MRAM 60 has a lower resistance than the second MRAM 62 then the voltages generated on the two nodes of the flip-flop, 70 and 71, would also be reversed. As a result a voltage of 0V would be applied to the liquid crystal capacitance in both the positive and negative refresh periods. This would cause the liquid crystal pixel to appear light.

While the pixel is being operated using data from the MRAM rather than data supplied via the column line the gate line is held at a low voltage in order to keep transistor 24 in a non-conducting state.

In the above described version of drive circuit 26, in some circumstances the status of the flip-flop may not be completely determined initially, or it may not be completely discharged between frames. This may leave remaining charge which may skew a read-out from the MRAMs. This is avoided or alleviated in another possible version of the drive circuit 26, in which the p-type TFT 76 and the n-type TFT 77 are omitted, i.e. the drive circuit instead comprises just the n-type TFT 75 and the n-type TFT 78. Then, although these TFTs 75, 78 may normally be alternated to change the polarity on the liquid crystal, they may instead both be switched on so as to reset the flip-flop circuit 64.

Thus the second MRAM 62 is arranged as and serves as a reference MRAM, that is it provides a reference by which the changed states of the switchable first MRAM 60 may be readily observed and measured in the form of a differential. This potentially allows relaxed manufacturing or other tolerances, since any variations due to manufacturing tolerances, or temperature of operation and so on that affect the switchable first MRAM 60 will tend also to be present for and affect in corresponding fashion the reference second MRAM 62.

Figure 6 shows a schematic diagram, not to scale, of the constructional layout employed for the pixel 20 in this embodiment. For clarity, the drive circuit 26, the polarity line 40, the refresh line 41 and the read line 42 are not shown. Indeed, the benefits of the constructional layout to be described below

are achieved independently of these items that are not shown. Those items already mentioned above which are shown in Figure 6 are the word line 43, the gate line 44, the TFT 24, the column line 54, the bit line 45, the pixel electrode 27 and the flip-flop circuit 64.

The various components and lines are each formed using conventional thin film deposition, masking and etching processes, as for conventional active matrix display devices. Figure 7 is a flowchart showing certain process steps used to form the in-pixel memory structure shown Figure 6.

At step s2, the word line 43 and the gate line 44 are formed in the same masking stage. Thus, advantageously, the word line 43, which is used in relation to operation of the in-pixel memory and would not be present in a conventional active matrix display device without in-pixel memory, is provided during a masking stage that is anyway needed for the conventional device (to provide the gate line 44), i.e. without the need for an additional masking stage. Also, the gate dielectric may be used to form a dielectric layer between the MRAM and the word line 43.

At step s4, the first MRAM 60 and the second MRAM 62 are formed as respective MRAM stacks above the word line 43, using a half tone mask. The positions of the MRAM stacks of the first MRAM 60 and the second MRAM 62, as viewed from above, are indicated by items 84 and 85 respectively.

At step s6 the bit line 45 and the column line 54 are formed in the same masking stage as each other. Thus, advantageously, the bit line 45, which is used in relation to operation of the in-pixel memory and would not be present in a conventional active matrix display device without in-pixel memory, is provided during a masking stage that is anyway needed for the conventional device (to provide the column line 54), i.e. without the need for an additional masking stage.

Also formed at step s6, i.e. this masking stage, are two connections hereinafter referred to as a first flip-flop connection 86 and a second flip-flop connection 87. The first flip-flop connection 86 connects the flip-flop circuit 64 to a first contact-via connected to the bottom of the first MRAM 60, i.e. effectively connects the first n-type TFT 68 of the flip-flop circuit 64 to the first

MRAM 60. The position of the first contact-via as viewed from above is shown by item 88 in Figure 6. Likewise, the second flip-flop connection 87 connects the flip-flop circuit 64 to a second contact-via connected to the bottom of the second MRAM 62, i.e. effectively connecting the second n-type TFT 69 of the flip-flop circuit 64 to the second MRAM 62. The position of the second contact-via as viewed from above is shown by item 89 in Figure 6. (Forming the contact-vias represents the second of the two additional mask steps, compared to a conventional active matrix display device, required in this embodiment to add the additional features shown in Figure 6.)

The bit line 45 is laid out such as to run from the TFT 24 (TFT 24 serves as the main addressing switching device for the pixel) to the pixel electrode 27. Included in this, the bit line is arranged to cross over the first MRAM 60 (seen in Figure 6 as crossing over the feature 84 which shows the position of the first MRAM 60 as viewed from above). This means that a current passing along the bit line 45 from the TFT 24 to the pixel electrode 27 passes or crosses over the first MRAM 60 as indicated by arrow 90 in Figure 6, so producing the required change in resistance state of the first MRAM 60.

Additionally, another optional advantageous feature is included in this embodiment in terms of the layout of the bit line 45 relative to the second MRAM 62, as follows. The bit line 45 is arranged to lie over the second MRAM 62, but not to pass over or cross over the second MRAM 62 in the sense of then continuing on to its eventual destination for the current flow (here the pixel electrode 27). This arrangement is seen in Figure 6 as the bit line 45 lying over the feature 85 which shows the position of the second MRAM 62 as viewed from above, but extending no further. This means that the current passing along the bit line 45 from the TFT 24 to the pixel electrode 27 does not pass or cross over the second MRAM 62, but instead bypasses it, as indicated by arrow 91 in Figure 6. This avoids or reduces overlap capacitance that might occur in other possible layouts where the bit line may, for example, pass over the second MRAM 62 en route to the pixel electrode 27.

Yet another advantageous feature is included in this embodiment, as follows. The word line 43 is positioned between the gate line 44 and the pixel

electrode 27. This means the bit line 45 does not need to pass over the gate line 44. This reduces the amount of overlap capacitance that would otherwise be caused by the bit line 45 overlapping the gate line 44. This usefully combines with the potential reduction in overlap capacitance discussed in the previous paragraph.

Further details of the construction of the in-pixel memory of this embodiment will now be described with reference to Figure 8 which shows a cross-section between the points X-X indicated on Figure 6. The word line 43 runs along the bottom of the section. A dielectric layer 94 is present over the word line 43, insulating the word line 43 from the MRAM (as mentioned earlier, this dielectric layer 94 may be formed using the gate dielectric layer). A conductor layer, which will serve as a MRAM contact extension 96, is provided on the dielectric layer 94. A further dielectric layer 95a, 95b, 95c is provided over and around the MRAM contact extension 96. The MRAM stack 97 of the first MRAM 60 is formed at one end of the MRAM contact extension 96. The bit line 45 is provided over the top of the MRAM stack 97. A contact-via 98 is provided above the other end of the MRAM contact extension 96. The first flip-flop connection 86 runs along the further dielectric layer 95a to the contact-via 98. Thus connection is made between the flip-flop circuit 64 and the MRAM stack 97, via the contact-via 98 and the MRAM contact extension 96. It will be appreciated that in other embodiments such connection can be made in any other convenient manner.

The present invention may be embodied using any appropriate MRAM stacks, for example simple ones as described above with reference to Figure 3. However, in this embodiment a preferred MRAM stack design is employed.

Figure 9 shows this preferred MRAM stack in cross-section (not to scale). The switchable form of the MRAM stack is described, but the same details, other than the polarisation directions of the free layer 102 and the pinned layer 106 apply also to the above described reference MRAM. The layers will now be described in the order they are deposited during formation of the MRAM stack, this being up the page as shown in Figure 9. The bottom contact is in this embodiment the previously described MRAM contact

extension 96, which extends beyond the edge of the rest of the MRAM stack to allow contact as described earlier. The MRAM contact extension 96 is an approximately 3.5nm thick Ta layer, and serves also as a buffer layer in terms of the mechanical properties and deposition process for the MRAM stack.

The next layer is a (conducting) layer 132 comprising an approximately 2nm thick layer of $Ni_{81}Fe_{19}$. The next layer is an exchange-biasing layer 134 comprising an approximately 20nm thick layer of $Pt_{50}Mn_{50}$.

The next layer is a pinned layer 106 (using the same reference numeral as in Figure 3), i.e. magnetic electrode. This pinned layer 106 is here made up of three layers, i.e. a first $Co_{90}Fe_{10}$ layer 136 of approximate thickness 3nm, a Ru layer 138 of approximate thickness 0.8nm and a second $Co_{90}Fe_{10}$ layer 140 of approximate thickness 3nm. The second $Co_{90}Fe_{10}$ layer 104 has the fixed magnetic orientation 110 described earlier in Figure 3. The first $Co_{90}Fe_{10}$ layer 136 has a fixed magnetic orientation 141 that is anti-parallel to the fixed magnetic orientation 110 of the second $Co_{90}Fe_{10}$ layer 104. The use of two such coupled layers instead of one single ferromagnetic layer is known in the art of ferromagnetism as using an artificial antiferromagnetic layer, also referred to as a synthetic ferrimagnet. Further details of the composition may be found in patent WO99/58994, which is incorporated herein by reference.

The next layer is a tunnel barrier layer 104 (using the same reference numeral as in Figure 3), which here comprises an approximately 0.8nm thick layer of oxidized Al.

The next layer is a free layer 102 (using the same reference numeral as in Figure 3). This free layer 102 is here made up of two layers, i.e. a $Co_{90}Fe_{10}$ layer of approximate thickness 4nm and a $Ni_{80}Fe_{20}$ layer of approximate thickness 10nm, with two switchable and opposing magnetic orientations shown by double-headed arrow 112 (using the same reference numeral as in Figure 3).

The next layer is a protective (conducting) layer 146 comprising an approximately 10nm thick Ta layer.

The top contact is provided by the bit line 45, as described earlier above.

The embodiment described above comprises a number of advantageous features in combination. However, in other embodiments many of these may be implemented singly or in any combination of two or more, as for example in the following cases.

In further embodiments, the circuit arrangements described with reference to Figure 2 and/or Figure 3 and/or Figure 4 and/or Figure 5 are employed, but with any suitable constructional layout and formed by any suitable deposition process being employed rather than those described above. Another possibility is for the MRAM and flip-flop arrangement to be as described above, but with any suitable drive circuit rather than the drive circuit described above. Another possibility is for a switchable MRAM and a reference MRAM to be employed with a read-out circuit other than a flip-flop circuit. Similarly, other read-out circuit designs, including other flip-flop circuit designs, and/or other MRAM stack designs, and/or pixel electrode details, and/or switching component details, and/or drive line details, and so on may be used instead of those described above.

For example, in the above embodiment, MRAMs based on tunnel barriers are used. However, in other embodiments, other types of MRAM, for example MRAMs based on giant magnetoresistance, or MRAMs based on the Hall-effect, may be used instead.

In further embodiments, more than one switchable MRAM and/or more than one reference MRAM may be provided for each pixel, and arranged in any suitable manner for providing for example increased read-out capability.

In other embodiments, in the deposition process, the word line is provided at the same stage as the gate line, for any suitable in-memory pixel design.

In other embodiments, in the deposition process, the bit line is deposited at the same stage as the column line, for any suitable in-memory pixel design.

In other embodiments, the bit line is positioned between the pixel electrode and the gate line, such that the bit line does not pass over the gate line, for any suitable in-memory pixel design.

In other embodiments the above possibilities may be applied to other types of active matrix.

In other embodiments the above possibilities may be applied to devices using other types of liquid crystal, or indeed any other suitable display device type, including for example plasma, polymer light emitting diode, organic light emitting diode, and field emission display devices.

In other embodiments, memory structures or circuits comprising two or more MRAMs and a read-out circuit may be employed in applications other than display devices. For example, they may be used for sensors, for example medical sensors. Another possibility is they may be used as embedded memories in integrated circuits.

CLAIMS

1. A memory circuit (25) comprising:

a switchable magnetoresistive random access memory, MRAM (60);

a reference MRAM (62); and

a read-out circuit (64);

the switchable MRAM and the reference MRAM each being coupled to the read-out circuit.

2. A memory circuit according to claim 1, wherein the switchable MRAM (60) comprises a free layer (102) and a pinned layer (106), a magnetic orientation of the free layer being switchable between two directions respectively substantially parallel to and anti-parallel to a magnetic orientation of the pinned layer; and

the reference MRAM (62) comprises a free layer (102a) and a pinned layer (106a), the free layer comprising two magnetic orientations each substantially perpendicular to a magnetic orientation of the pinned layer.

3. A memory circuit according to claim 2, wherein the free layers (102, 102a) of the switchable MRAM and the reference MRAM are formed from a same deposition layer and/or the pinned layers (106, 106a) of the switchable MRAM and the reference MRAM are formed from a same deposition layer.

4. A memory circuit according to any of claims 1 to 3, wherein the read-out circuit is a flip-flop circuit.

5. A memory circuit according to claim 4, wherein the flip-flop circuit comprises two inputs, the switchable MRAM (60) being coupled to one of the inputs and the reference MRAM (62) being coupled to the other of the inputs.

6. A display device comprising a plurality of pixels (20 – 23) and a plurality of memory circuits according to any of claims 1 to 5, each pixel being associated with a respective one of the memory circuits.

7. A pixel (20) and in-pixel memory (25) for a display device, comprising:

a switching device (24);

a pixel electrode (27);

a switchable MRAM (60);

a reference MRAM (62); and

a bit line (45), the bit line running from the switching device to the pixel electrode;

the bit line crossing over one end of the switchable MRAM and being positioned over but not crossing over one end of the reference MRAM.

8. A pixel (20) and in-pixel memory (25) according to claim 7, further comprising a word line (43) running under the other ends of each of the switchable MRAM and the reference MRAM.

9. A pixel and in-pixel memory according to claim 8, further comprising a gate line (44), for driving the switching device (24), coupled to the switching device; and wherein the word line is arranged between the pixel electrode and the gate line such that the bit line passes over the word line but does not pass over the gate line.

10. A pixel and in-pixel memory according to claim 9, further comprising a read-out circuit (64) coupled to the switchable MRAM (60) and the reference MRAM (62).

11. A pixel and in-pixel memory according to any of claims 7 to 10, wherein the switchable MRAM (60) comprises a free layer (102) and a pinned layer (106), a magnetic orientation of the free layer being switchable between

two directions respectively substantially parallel to and anti-parallel to a magnetic orientation of the pinned layer; and

the reference MRAM (62) comprises a free layer (102a) and a pinned layer (106a), a magnetic orientation of the free layer being switchable between two directions each substantially perpendicular to a magnetic orientation of the pinned layer.

12. A pixel and in-pixel memory according to claim 11, wherein the free layers of the switchable MRAM and the reference MRAM are formed from a same deposition layer and/or the pinned layers of the switchable MRAM and the reference MRAM are formed from a same deposition layer.

13. A pixel and in-pixel memory according to any of claims 10 to 12, wherein the read-out circuit is a flip-flop circuit.

14. A pixel and in-pixel memory according to claim 13, wherein the flip-flop circuit comprises two inputs, the switchable MRAM being coupled to one of the inputs and the reference MRAM being coupled to the other of the inputs.

15. A display device (1) comprising a pixel and in-pixel memory according to any of claims 7 to 14.

16. A display device according to claim 15, wherein the pixel and in-pixel memory is integrated with active matrix elements (24) and drive lines (40 – 44, 47 – 51, 54, 55) of the display device.

17. A method of forming a memory arrangement, comprising forming a switchable MRAM (60) and a reference MRAM (62) from one or more common deposition layers.

18. A method according to claim 17, wherein the switchable MRAM is formed so as to comprise a free layer and a pinned layer, a magnetic orientation of the free layer being switchable between two directions respectively substantially parallel to and anti-parallel to a magnetic orientation of the pinned layer; and the reference MRAM is formed so as to comprise a free layer and a pinned layer, the free layer comprising two magnetic orientations each substantially perpendicular to a magnetic orientation of the pinned layer.

19. A method according to claim 17 or 18, further comprising forming a read-out circuit (64) coupled to the MRAMs.

20. A method according to claim 19, wherein the read-out circuit is a flip-flop circuit.

21. A method according to any of claims 17 to 20, wherein the MRAMs are formed as part of an active matrix for a display device.

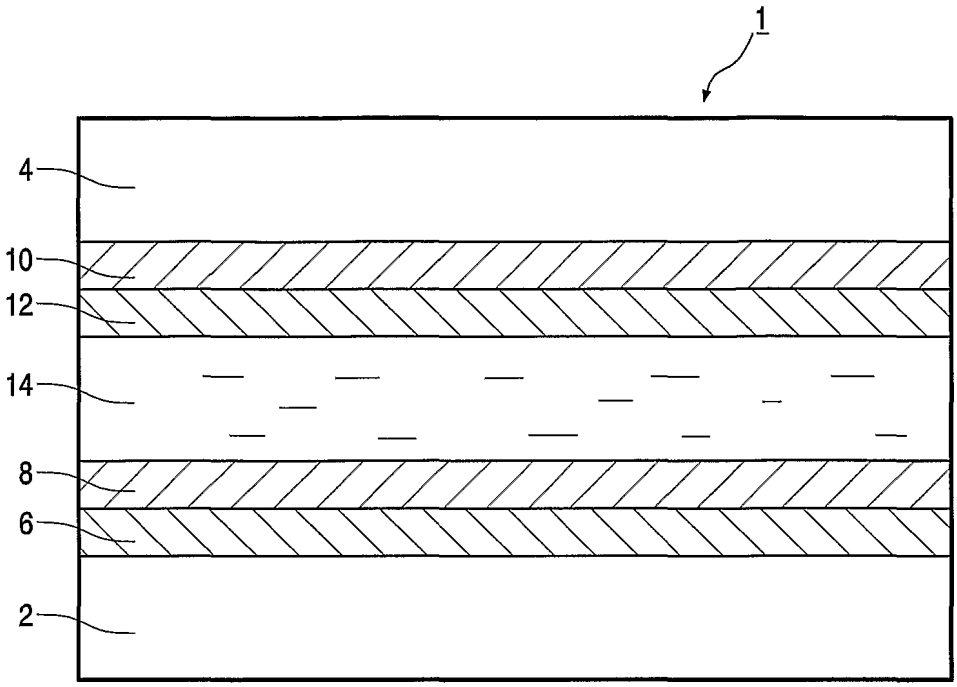

FIG.1

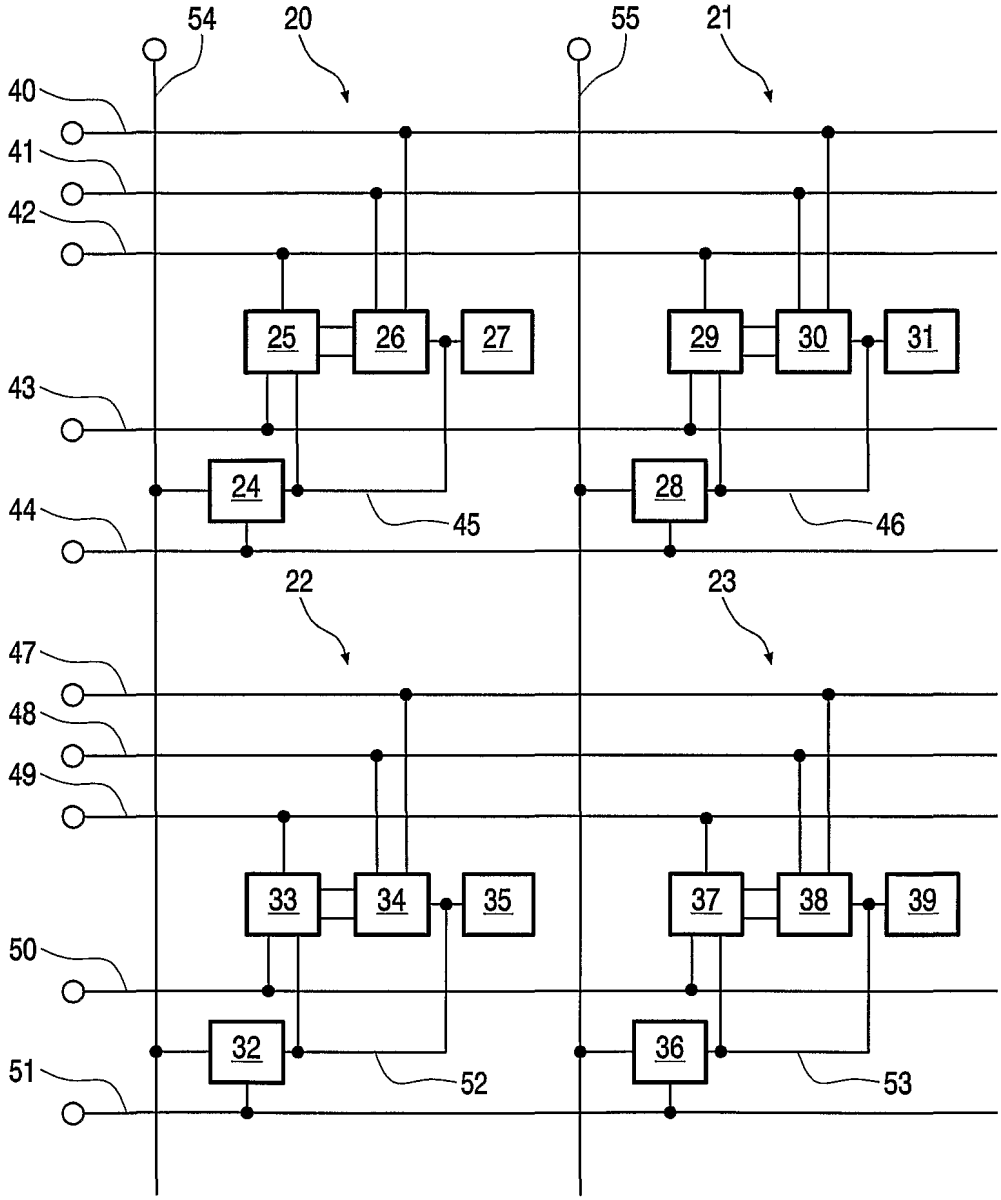
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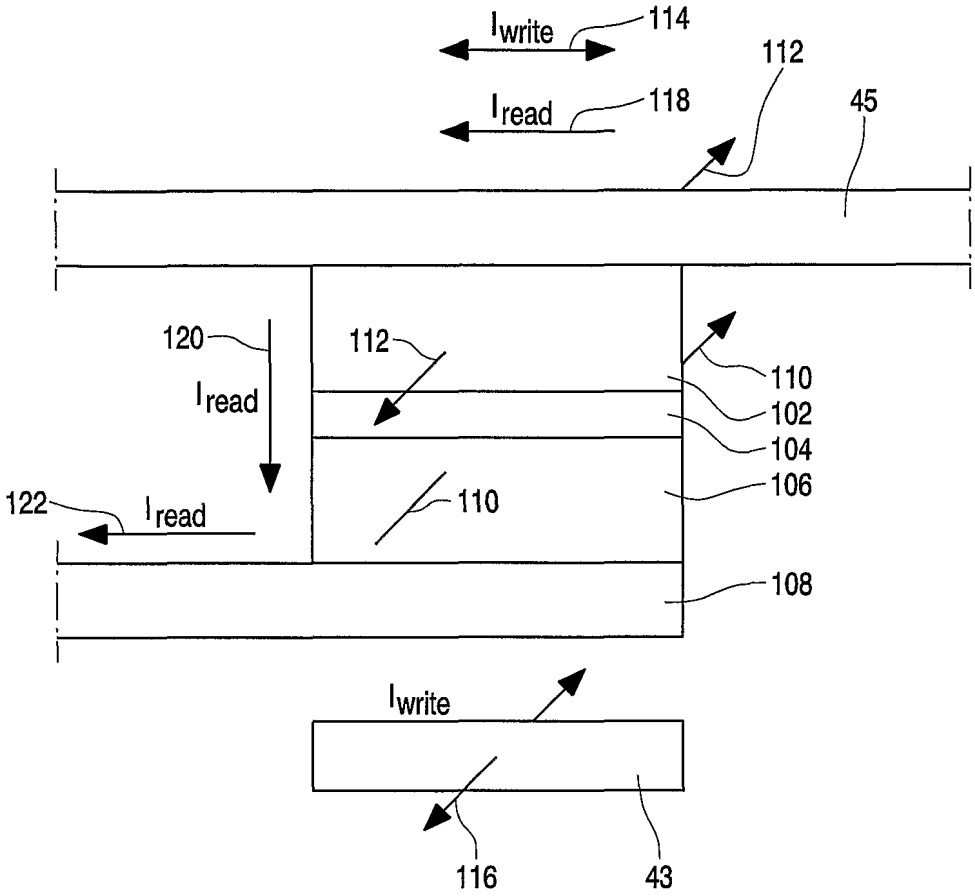
FIG.2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114
112
I read
118
45
120
112
I read
110
102
104
122
I read
110
106
108
I write
116
43

FIG.3

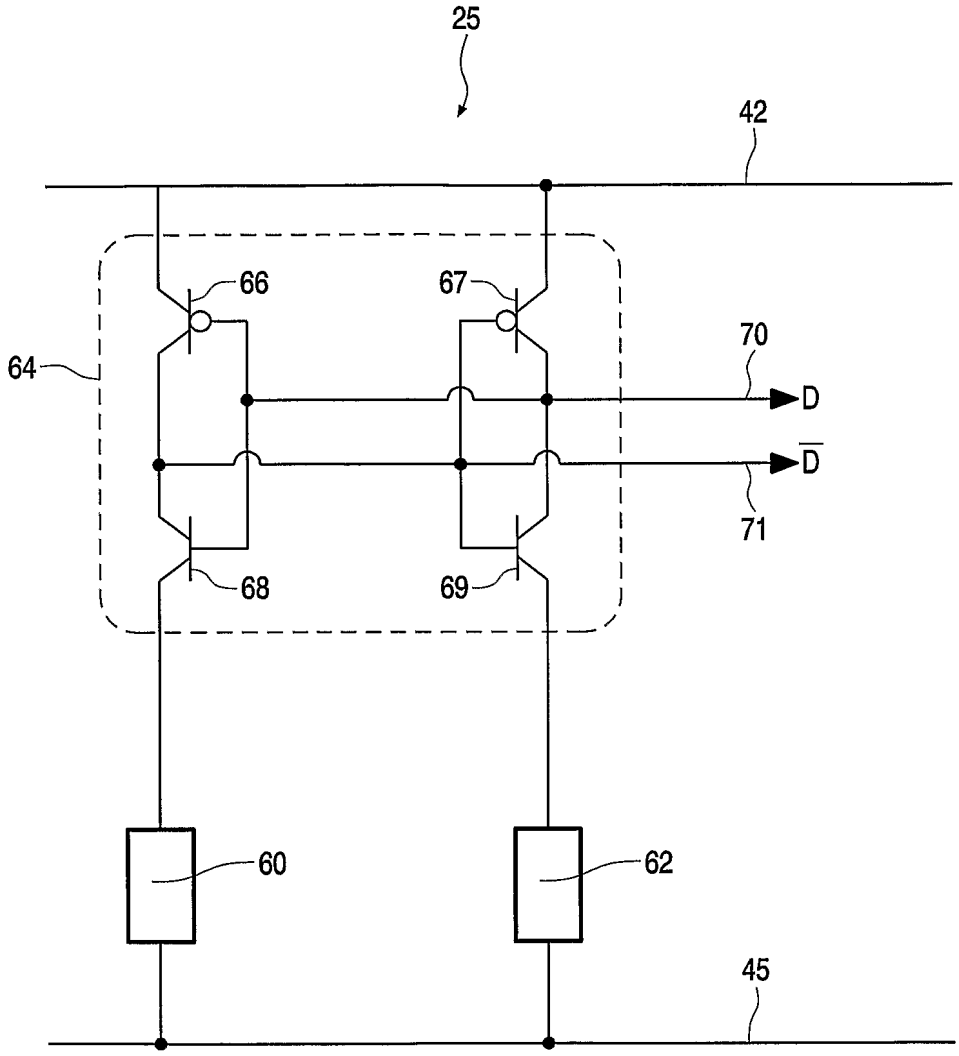
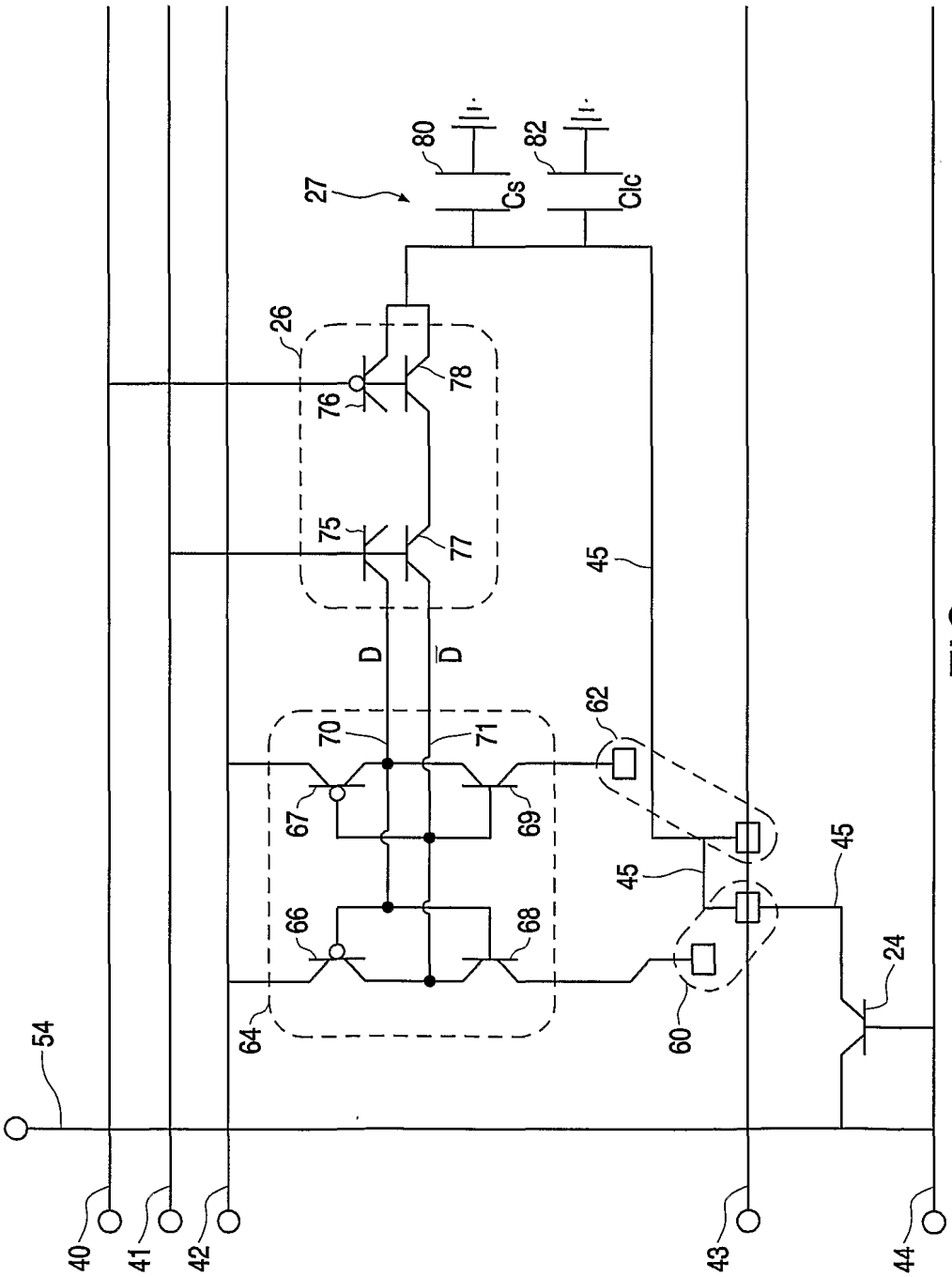


FIG.4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Clc
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45
D
D
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24
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FIG.5

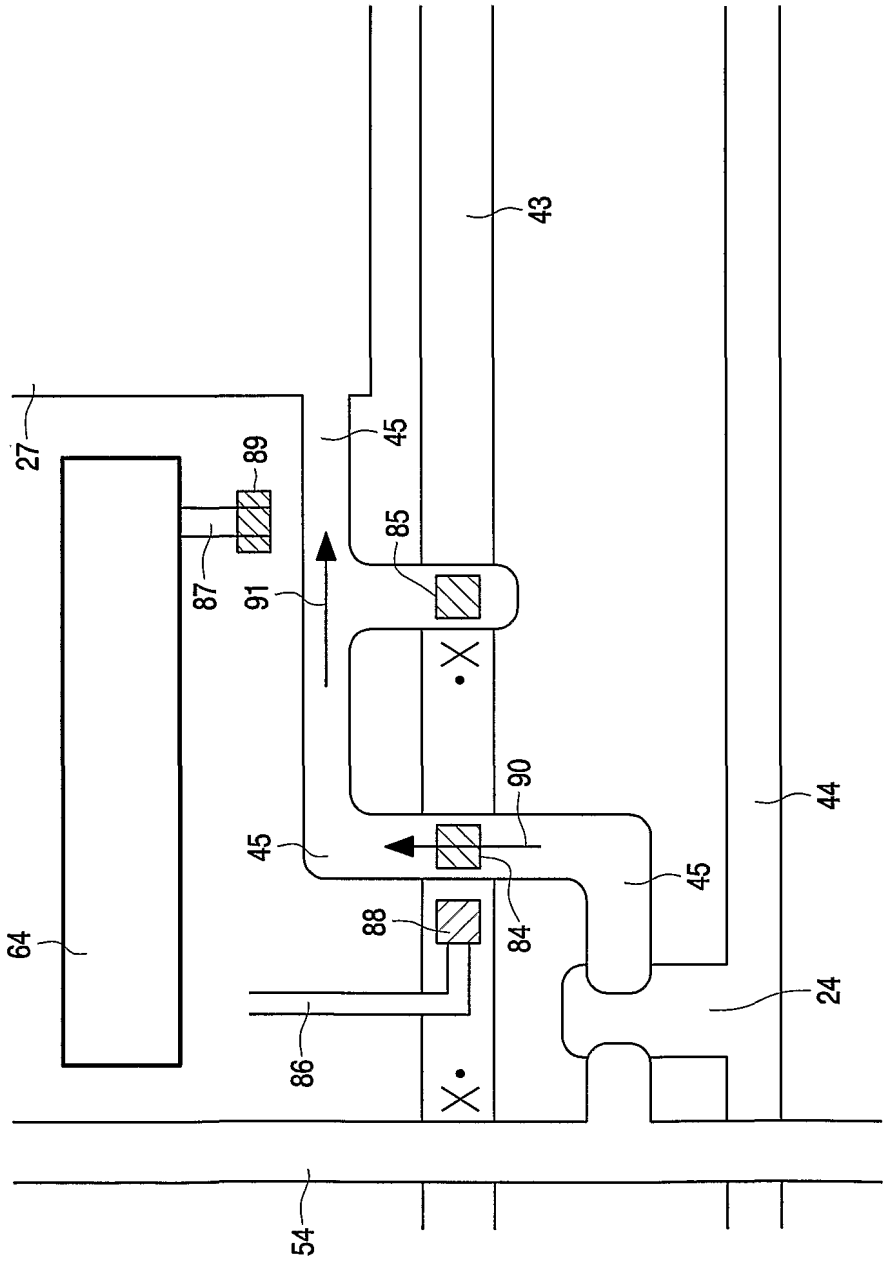


FIG.6

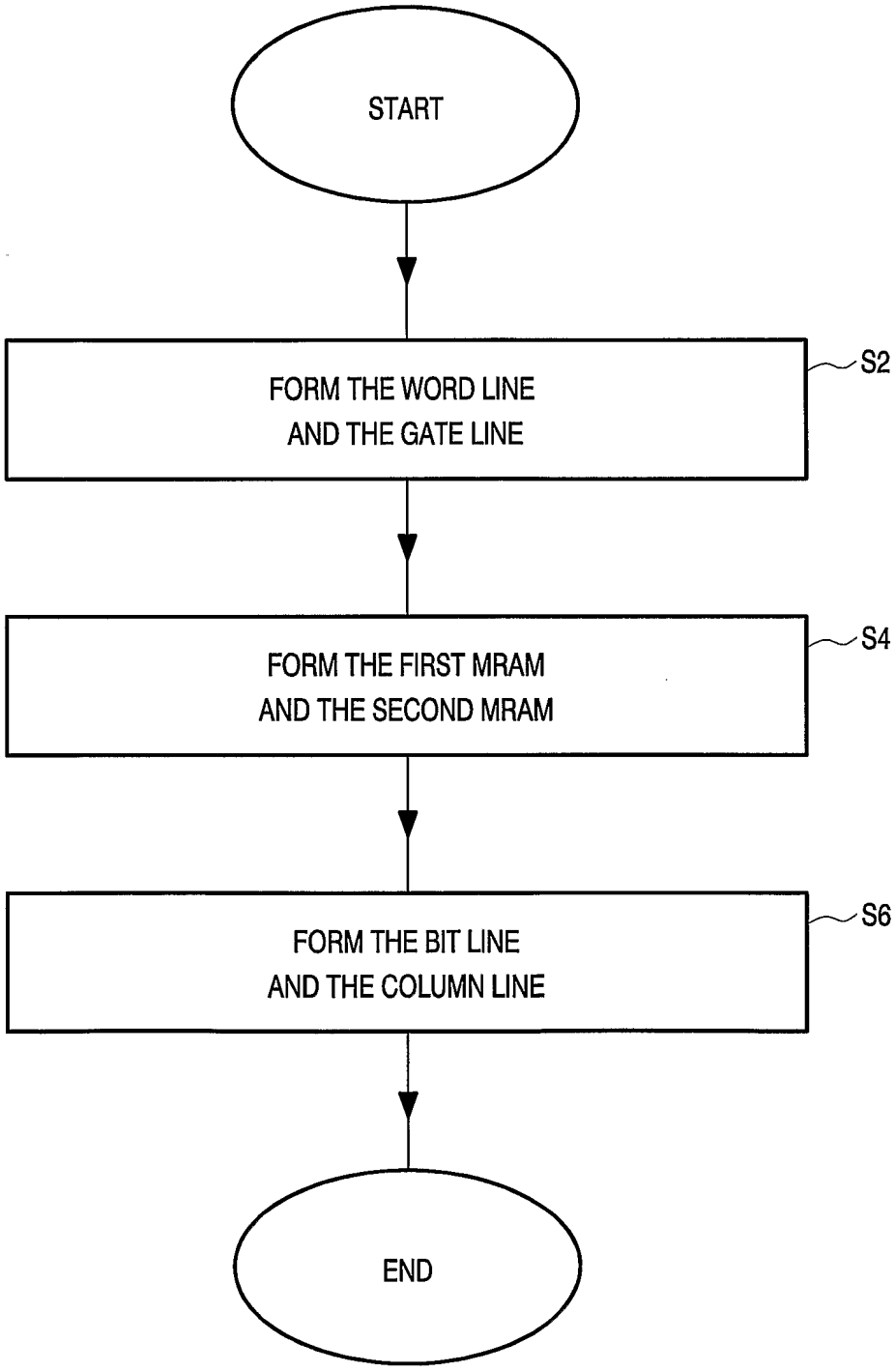

START
FORM THE WORD LINE
AND THE GATE LINE
S2
FORM THE FIRST MRAM
AND THE SECOND MRAM
S4
FORM THE BIT LINE
AND THE COLUMN LINE
S6
END

FIG.7

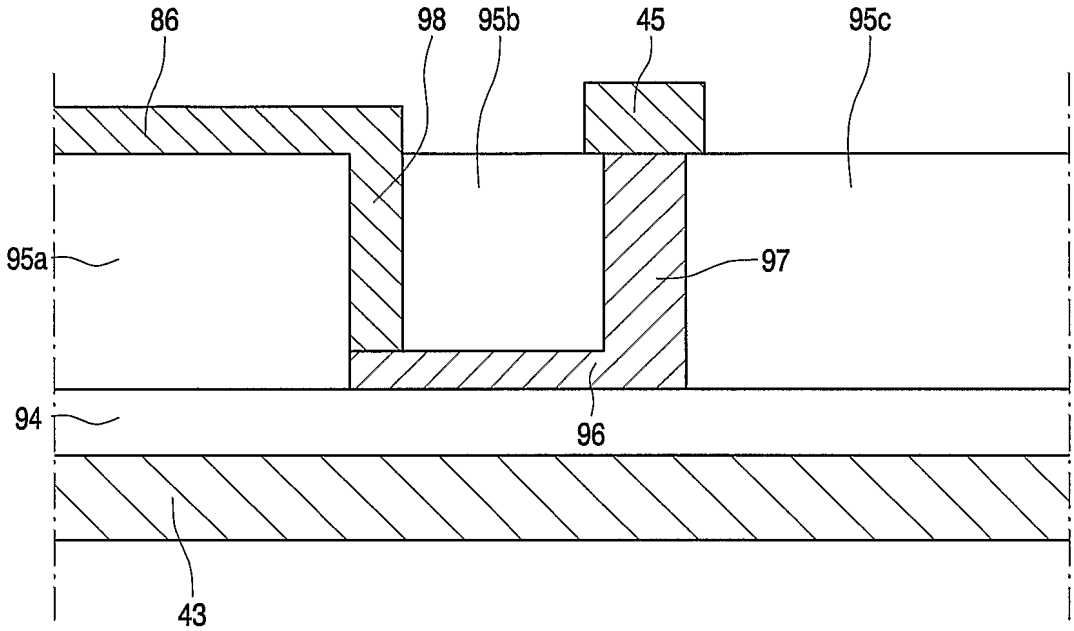
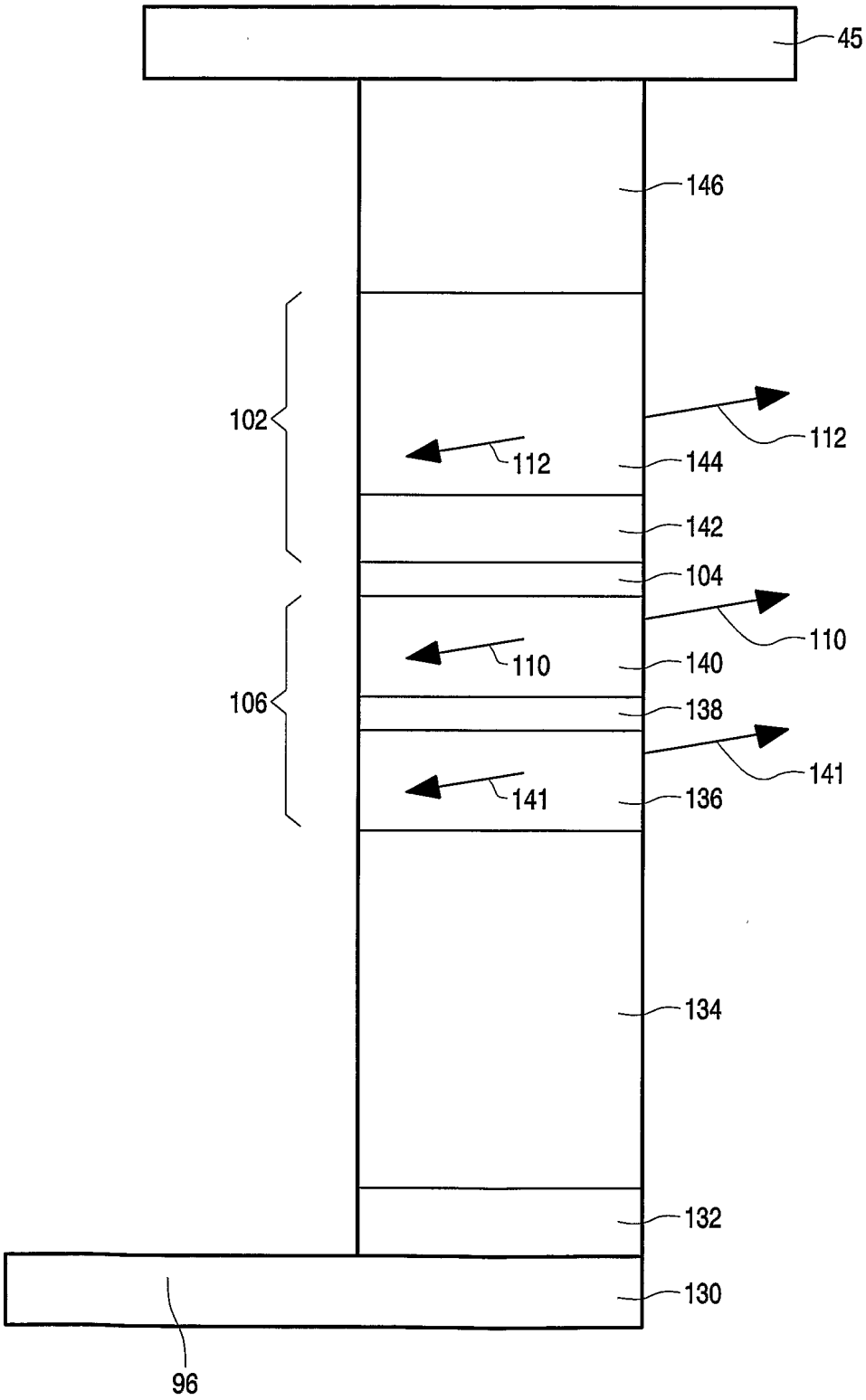


FIG.8


45
146
102
112
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144
142
104
110
110
140
106
138
141
141
136
134
132
130
96

FIG.9

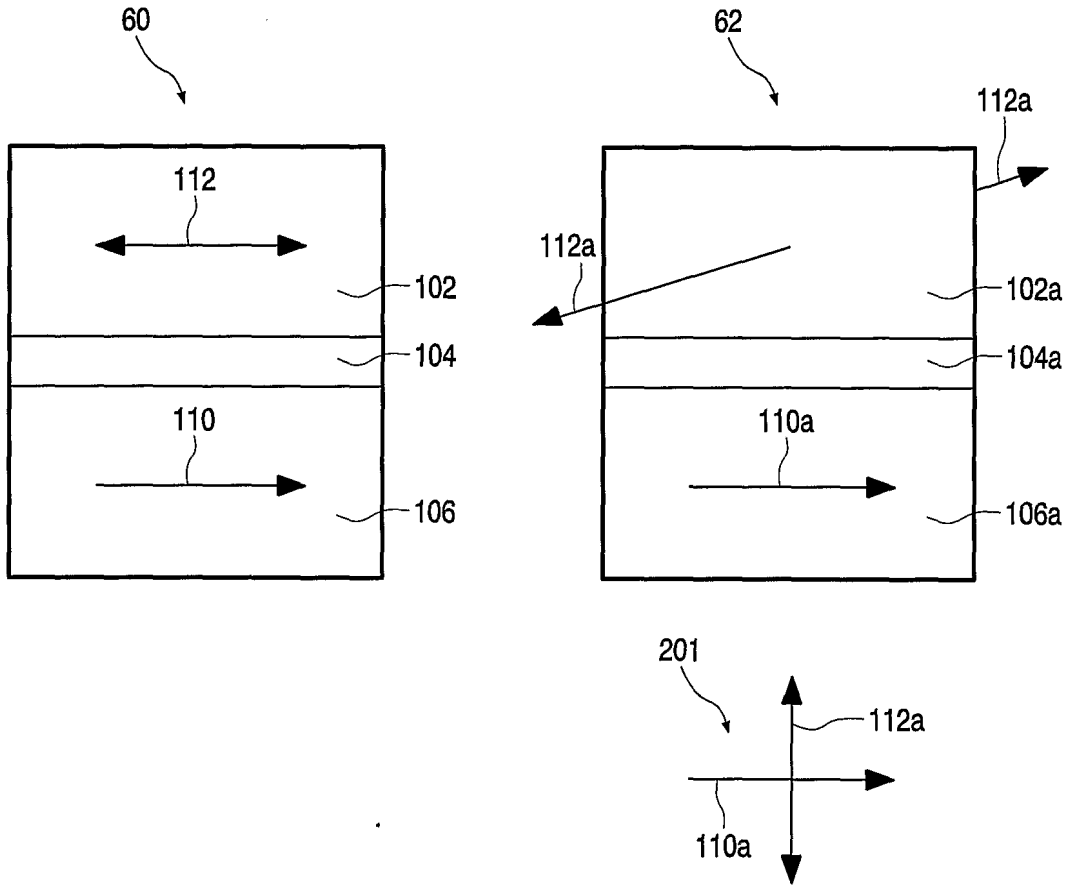
60
112
102
104
110
106
62
112a
112a
102a
104a
110a
106a
201
112a
110a

FIG.10