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(74) Agents: KWON, Hyuk-Soo et al.; 3rd Fl., Yeoksam-dong, Kangnam-ku, Seoul 135-080 (KR).

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(71) Applicant (for all designated States except US): INHA INDUSTRY PARTNERSHIP INSTITUTE [KR/KR]; 253, Yong-Hyun-dong, Nam-gu, Incheon, 402-823 (KR).

(72) Inventor; and

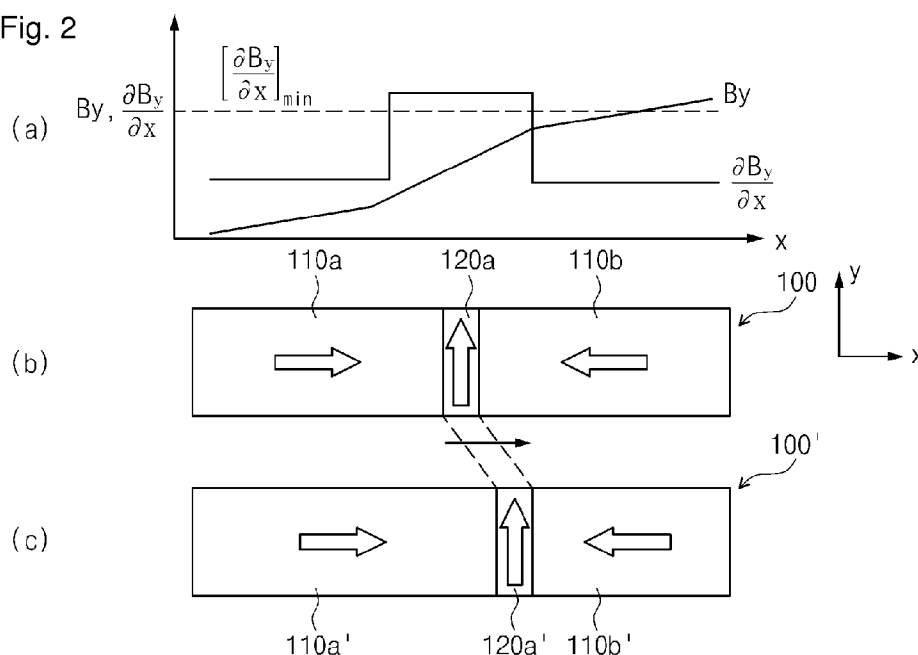
(75) Inventor/Applicant (for US only): YOU, Chun Yeol [KR/KR]; #115-1001, Dong-a Apt., Dongchun-dong, Yeonsu-gu, Incheon, 406-130 (KR).

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(54) Title: MAGNETIC FLUX DENSITY DRIVEN MAGNETIC DOMAIN WALL MOVING MEMORY DEVICE, OPERATING METHOD OF THE SAME, AND FORMING METHOD OF THE SAME

Fig. 2



(57) Abstract: Disclosed is a magnetic flux density driven magnetic domain wall movement memory device, and operating and forming methods thereof. The memory device is comprised of a data storage pattern including pluralities of magnetic domain walls and at least a magnetic domain, and at least a driving pattern generating a driving magnetic flux density for the data storage pattern. The magnetic domain wall of the data storage pattern shifts by the driving magnetic flux density.

## **Description**

# **MAGNETIC FLUX DENSITY DRIVEN MAGNETIC DOMAIN WALL MOVING MEMORY DEVICE, OPERATING METHOD OF THE SAME, AND FORMING METHOD OF THE SAME**

### **Technical Field**

- [1] The present invention relates to memory devices and more particularly, to magnetic flux density driven magnetic domain wall moving memory device.

### **Background Art**

- [2] There are various kinds of storage devices, such as dynamic random access memories, static random access memories, flash memories, magnetic hard disks, and so on. Flash memories operate on the merits of nonvolatile property, but expensive and disadvantageous to large capacity. Magnetic hard disks are easy to provide high recording density in nonvolatility, but weak to physical impacts because they operate with mechanical heads. Therefore, such hard disks are considered as improper to mobile or portable storage devices.
- [3] In the mean time, current driven magnetic domain wall movement memory devices is comprised of data storage patterns having pluralities of magnetic domains. The magnetic domains can be divided by boundaries that are magnetic domain walls, which may be different from each other in directions of magnetization. When predetermined current flows through the data storage pattern, data recorded in a magnetic domain is continuously transferred toward adjacent magnetic domains. This effect is called current driven magnetic domain wall movement (hereinafter, referred to as 'current-driven MDWM'. However, the current-driven MDWM memory devices are slow in moving magnetic domains or magnetic domain wall, so insufficient to be used as storage devices.

### **Disclosure of Invention**

#### **Technical Problem**

- [4] The present invention is accordingly directed to a MDWM memory device that can be used for a large capacity memory device, be protected against an external impact, and realize a high-speed performance.
- [5] The present invention is also directed to an operating method of a MDWM memory device that can be used for a large capacity memory device, be protected against an external impact, and realize a high-speed performance.
- [6] The present invention is also directed to a forming method of a MDWM memory device that can be used for a large capacity memory device, be protected against an

external impact, and realize a high-speed performance.

### **Technical Solution**

- [7] An aspect of the present invention is a memory device is comprised of: a data storage pattern including pluralities of magnetic domains and magnetic domain walls; and at least a drive pattern generating a driving magnetic flux density for the data storage pattern. The magnetic domain walls of the data storage pattern shifts by the driving magnetic flux density.
- [8] According to an embodiment, the driving magnetic flux density varies in intensity by positional variation along a progress direction of the data storage pattern.
- [9] According to an embodiment, the magnetic domain walls of the data storage pattern are conditioned in the same magnetization direction.
- [10] According to an embodiment, the memory device is further comprised of a magnetic domain wall aligning structure aligning the magnetic domain walls of the data storage pattern to the same magnetization direction.
- [11] According to an embodiment, the driving magnetic flux density operates in spatially periodic distribution along a progress direction of the data storage pattern.
- [12] According to an embodiment, the magnetic domain walls are vertical to the magnetic domains in magnetization direction.
- [13] According to an embodiment, the magnetization directions of the magnetic domains are parallel or anti-parallel to a progress direction of the data storage pattern.
- [14] According to an embodiment, the memory device is further comprised of a writing structure disposed around the data storage pattern and changing a magnetization direction of the magnetic domain.
- [15] According to an embodiment, the writing structure magnetizes the magnetic domains to be parallel or anti-parallel with a progress direction of the data storage pattern.
- [16] According to an embodiment, the memory device is further comprised of a re-producing structure disposed around the data storage pattern and reading the magnetization directions of the magnetic domains.
- [17] According to an embodiment, the data storage pattern comprises pluralities of unit areas arranged along a progress direction of the data storage pattern. Each unit area includes a unit magnetic domain, or a unit magnetic domain and a magnetic domain wall adjacent to the unit magnetic domain. The driving magnetic flux density operates in distribution with a spatial period that corresponds to a length of the unit area or integer times of the length along a progress direction of the data storage pattern.
- [18] According to an embodiment, the drive pattern is included in plurality with respect to the unit areas. The drive patterns respective to the unit areas are same with each other in structure.

- [19] According to an embodiment, the driving magnetic flux density at least has the maximum point or a point changing a sign of a gradient of the driving magnetic flux density.
- [20] According to an embodiment, the driving magnetic flux density is less than the maximum intensity for changing a magnetization direction of the magnetic domain and higher than the minimum intensity for shifting the magnetic domain wall.
- [21] According to an embodiment, the data storage pattern comprises at least one of ferromagnetic, ferromagnetic alloy, and ferrimagnetic materials.
- [22] According to an embodiment, the data storage pattern comprises at least one of nonmagnetic and anti-ferromagnetic materials.
- [23] According to an embodiment, the data storage pattern is shaped in one of a strip line, an open loop, and a serpentine form.
- [24] According to an embodiment, the drive pattern intersects a progress direction of the data storage pattern in a predetermined angle.
- [25] According to an embodiment, the drive pattern has an uneven width for irregular spatial distribution.
- [26] According to an embodiment, the drive pattern extends along a progress direction of the data storage pattern so as to periodically apply the driving magnetic flux density along the progress direction of the data storage pattern. The drive pattern varies in one of width and thickness so as to periodically apply the driving magnetic flux density.
- [27] According to an embodiment, the data storage pattern further comprises a pinning region for pinning the magnetic domain wall.
- [28] According to an embodiment, the pinning region is different from an adjacent region of the pinning region in at least one of width, thickness, material, curvature, and physical property.
- [29] According to an embodiment, the memory device is further comprised of a pinning structure disposed around the drive pattern. The pinning structure includes at least one of a multi-level film, a spring magnet, an anti-ferromagnetic material, and a soft magnetic material.
- [30] According to an embodiment, the memory device is further comprised of a shielding structure disposed around the drive pattern and shielding the driving magnetic flux density generated by the drive pattern.
- [31] According to an embodiment, the memory device is further comprised of a soft magnetic pattern interposed between the data storage pattern and the drive pattern, changing spatial distribution of the driving magnetic flux density generated by the drive pattern. The soft magnetic pattern is configured to make the driving magnetic flux density change in intensity by positional variation along a progress direction of the data storage pattern.

- [32] Another aspect of the present invention is an operating method of the memory device comprised of: a data storage pattern including pluralities of magnetic domain walls and at least a magnetic domain; and at least a driving pattern generating a driving magnetic flux density for the data storage pattern. The magnetic domain wall of the data storage pattern shifts by the driving magnetic flux density. A current flowing through the drive pattern varies by time.
- [33] Another aspect of the present invention is an operating method of the memory device comprised of: a data storage pattern including pluralities of magnetic domain walls and at least a magnetic domain; and at least a driving pattern generating a driving magnetic flux density for the data storage pattern. The magnetic domain wall of the data storage pattern shifts by the driving magnetic flux density. A current flowing through the drive pattern is applied in a pulse.
- [34] The present invention also provides a forming method comprised of: forming a data storage pattern including pluralities of magnetic domains and magnetic domain walls on a substrate; and forming at least one drive pattern, for generating a driving magnetic flux density, around the data storage pattern. The driving magnetic flux density enables the magnetic domain wall of the data storage pattern to shift.
- [35] A further understanding of the nature and advantages of the present invention herein may be realized by reference to the remaining portions of the specification and the attached drawings.

### **Advantageous Effects**

- [36] According to the present invention, driving magnetic flux density is unevenly applied to a data storage pattern. Thereby, magnetic domain walls move in the data storage pattern. Owing to this effect, the data storage pattern can be used as storage means. Such a magnetic flux density driven MDWM (hereinafter, referred to as 'MFD-driven MDWM' memory device is nonvolatile with fast shift of the magnetic domain walls. Thus, it is proper to large storage capacity.

### **Brief Description of the Drawings**

- [37] FIG. 1 is a schematic view illustrating an operating feature of an MFD-driven MDWM memory device in accordance with an embodiment of the present invention.
- [38] FIGs. 2 is view illustrating a shift of magnetic domain walls when the magnetic flux density is unevenly applied to the MFD-driven MDWM memory device of the present invention.
- [39] FIGs. 3 is view illustrating movement of magnetic domain walls when the driving magnetic flux density is unevenly applied to the MFD-driven MDWM memory device of the present invention.
- [40] FIGs. 4 and 5 are schematic views illustrating magnetization directions of magnetic

domain walls and magnetic domains in the MFD-driven MDWM memory device of the present invention.

- [41] FIGs. 6 and 7 are schematic views illustrating a method of forming magnetic domain walls oriented in the same magnetization direction in the MDWM memory device of the present invention.
- [42] FIGs. 8 through 10 are schematic views illustrating a procedure for aligning magnetic domain walls in the MFD-driven MDWM memory device of the present invention.
- [43] FIGs. 11 through 13 are schematic views illustrating features of pinning in the MFD-driven MDWM memory device of the present invention.
- [44] FIGs. 14 through 16 are schematic views illustrating structures of data storage patterns in the MFD-driven MDWM memory device of the present invention.
- [45] FIGs. 17 through 20 are schematic views illustrating shapes of data storage patterns in the MFD-driven MDWM memory device of the present invention.
- [46] FIGs. 21 and 22 are schematic views illustrating shielding structures of the MFD-driven MDWM memory device of the present invention.
- [47] FIGs. 23 and 24 are schematic views illustrating drive patterns of the MFD-driven MDWM memory device of the present invention.
- [48] FIGs. 25 and 26 are schematic views illustrating patterns of soft magnetic material in the MFD-driven MDWM memory device of the present invention.
- [49] FIG. 27 is a flow chart showing a procedure of shifting the magnetic domain walls in accordance with an embodiment of the present invention.
- [50] FIGs. 28 is view illustrating features of shifting the magnetic domain walls, showing the data storage pattern (28A), the drive magnetic flux density for moving the magnetic domain walls to right (28B), and the drive magnetic flux density for shifting the magnetic domain walls to left (29C), respectively, in accordance with an embodiment of the present invention.
- [51] FIGs. 29 is view illustrating a feature of shifting the magnetic domain walls of the data storage pattern in accordance with an embodiment of the present invention.

### **Mode for the Invention**

- [52] Responding to magnetic flux density unevenly applied to a data storage pattern, magnetic domain walls are able to continuously move toward adjacent magnetic domains. In this description, such an effect will be called 'magnetic flux density driven magnetic domain wall movement' (referred to as MFD-driven MDWM). The present invention provides a memory device using the MFD-driven MDWM, i.e., an MFD-driven MDWM.
- [53] Magnetization directions of magnetic domains may be changed by magnetic flux density applied from a writing structure disposed at a side of the data storage pattern,

and conditioned in one of parallel or anti-parallel states. This alternativeness of the parallel and anti-parallel states in the magnetization direction of the magnetic domains can be used for representing binary data.

- [54] During this, as the magnetic domains act as independent regions in which data are stored, a plurality of data can be recorded in a data storage pattern. Additionally, the magnetic domain can be divided into pluralities of unit magnetic domains each of which stores data. Considering that the magnetic domains are successively arranged on the boundaries of magnetic domain walls, the MDWM memory device is more advantageous in high data storage density than a flash memory device which needs spatial isolation between regions (e.g., floating gate electrodes) for storing data. Moreover, the MDWM memory device is able to operate even without transistors that are formed on semiconductor crystal, which makes it easy to employ a 3-dimensional stacked structure therein.
- [55] The MFD-driven MDWM effect changes locations of magnetic domains in which data are recoded, without impairing data recorded in the magnetic domains of the data storage pattern. By way of the MFD-driven MDWM effect, there is no need of mechanically moving a recording electrode structure as like a magnetic hard disk in order to change data of a predetermined unit magnetic domain. Thus, the MFD-driven MDWM memory device is strong against an external impact.
- [56] In detail, such a data change is carried out through the procedure of moving data, which is to be modified, into a unit domain adjacent to a writing structure by way of the MFD-driven MDWM effect and modifying the data by means of the writing structure.
- [57] And, data reproduction is carried out through the procedure of moving data, which is to be read, into a unit magnetic domain adjacent to a reproducing structure and reading the data by means of a reproducing structure.
- [58] The MFD-driven MDWM memory device according to the present invention is operable in higher data moving speed than the conventional current-driven MDWM memory device, advantageous to nonvolatile and mobile large-capacity storage.
- [59] Hereinafter, preferred embodiments of the present invention will be described below in more detail with reference to the accompanying drawings. The present invention may, however, be embodied in different forms and should not be constructed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the present invention to those skilled in the art. In the figures, the dimensions of layers and regions are exaggerated for clarity of illustration. It will also be understood that when a layer (or film) is referred to as being 'on' another layer or substrate, it can be directly on the other layer or substrate, or intervening layers may also be present. Like

reference numerals refer to like elements throughout the accompanying figures. Over this specification, arrows representing directions of magnetization are also correspondent to the representative directions of magnetization in magnetic domain walls or magnetic domains, but detailed or microscopic directions of magnetization will not be illustrated.

- [60] FIG. 1 is a schematic view illustrating an operating feature of the MFD-driven MDWM memory device in accordance with an embodiment of the present invention.
- [61] The MFD-driven MDWM memory device is comprised of a data storage pattern 100, and a drive pattern (not shown) for applying magnetic flux density to the data storage pattern 100. The data storage pattern 100 is divided into pluralities of magnetic domains 110 and magnetic domain walls 120. The magnetic domain wall 120 is interposed between the adjacent magnetic domains 110 forming a pair, but different to each other in magnetization direction. The magnetic domains 110 and the magnetic domain walls 120 can be shifted to other locations in the data storage pattern 100.
- [62] The magnetic domain 110 may include at least one or more unit magnetic domains. The unit magnetic domain means the least area for storing data. The magnetic domain 110 exemplarily includes two unit magnetic domains 110b and 110c. It is permissible to form the unit magnetic domains 110b and 110c without the magnetic domain wall 120 therebetween.
- [63] The data storage pattern 100 is comprised of plural unit areas each of which includes a single unit district 110a. If magnetization directions are different from the unit magnetic domains 110a and 110b successive to each other, the unit area may include more one magnetic domain wall 120 formed at a side of the magnetic domain 110. The unit area is referred to 'unit cell'.
- [64] If the unit magnetic domains 110b and 110c are continuously arranged along the same magnetization direction, the magnetic domain wall 120 may not be present between the unit magnetic domains. In this case, the unit cell may include only the unit magnetic domain 110b.
- [65] Referring to FIG. 1, the data storage pattern 100 may be made in the form of nano wire. Herein, a direction of arranging the unit areas is referred to 'progress direction'. The progress direction is variable in accordance with a location of the data storage pattern 100.
- [66] The progress direction according to an embodiment of the present invention may be along the X axis. And, the data storage pattern 100 may be configured in a pre-determined thickness  $t$  and width  $w$ . The data storage pattern 100 may be shaped in a strip line. Cutting the data storage pattern 100 off vertically to the progress direction, the section may be shaped in a rectangle. But, even unless the section is a rectangle, it is able to approximate the section as the rectangle. And, a plane of the data storage

pattern 100 is defined by unit vectors along the width and progress directions at each magnetic domain 110.

- [67] As illustrated in FIG. 1, the data storage pattern 100 may be formed of the plural magnetic domains 110 and the magnetic domain walls 120 between the magnetic domains 110. The adjacent magnetic domains 110 may be contrary to each other in magnetization direction. In this condition, the magnetization direction of the magnetic domain wall 120 between the adjacent magnetic domains 110 may be set to minimize the total systemic energy summed up by exchange interaction energy between the adjacent magnetic domains, magnetic anisotropy energy, and magnetostatic energy. Further, the magnetization direction of the magnetic domain wall 120 may be determined by a topological structure with thickness and width, a quantity of saturated magnetization of the data storage pattern 100, and magnetic anisotropy energy.
- [68] The magnetic domain wall may be divided into a Neel, Bloch, or vortex types. For the inplane magnetization case, a magnetization direction of the Bloch magnetic domain wall may be vertical to the plane of the data storage pattern 100. A magnetization direction of the Neel magnetic domain wall may be parallel with the plane of the data storage pattern 100. A magnetization direction of the vortex wall may be parallel with the data storage pattern 100, while magnetization of its core part are vertical to the plane. For the perpendicular magnetic anisotropy materials, the details of the Neel, Bloch wall are changed. But, the Bloch and Neel magnetization domain walls may be vertical to that of the adjacent magnetic domains 110. The magnetic domain wall 120 can be set by controlling a thickness, width, material, and temperature of the data storage pattern 100.
- [69] Continued on FIG. 1, the data storage pattern 100 may be shaped in a strip line. The magnetization direction of the magnetic domains may be parallel or anti-parallel to the progress direction. The magnetization direction of the magnetic domain wall may be along the +Y or -Y axis. In the meantime, it is assumed that on the data storage pattern 100, a magnetic flux density along the Y axis is  $B_y$ . If  $B_y$  has a gradient

$$\frac{\partial B_y}{\partial x},$$

a force acting to the magnetic domain wall 120 of the data storage pattern 100 may be approximated in.

[70] [Equation 1]

[71]

$$\vec{F} = \nabla(\vec{m} \cdot \vec{B}) = \left( \frac{\partial}{\partial x} \hat{a}_x + \frac{\partial}{\partial y} \hat{a}_y + \frac{\partial}{\partial z} \hat{a}_z \right) (m_x B_x + m_y B_y + m_z B_z)$$

[72] [Equation 2]

[73]

$$\vec{F} \approx m_y \left( \frac{\partial B_y}{\partial x} \right) \hat{a}_x$$

[74] Here, if it approximates the magnetization direction of the magnetic domain wall 120 only with a Y axis component without considering an X axis component of the magnetic domain 110, the force toward the magnetic domain wall 120 is summarized as shown by Equation 2. In Equation 1,

$$\vec{m}$$

is a magnetic dipole moment and

$$\vec{B}$$

is a magnetic field or magnetic flux density.

[75] If

$$\vec{B}$$

has a Y axis component and

$$\frac{\partial B_y}{\partial x}$$

is valued in a positive, the magnetization domain wall 120 magnetized the +Y axis with the magnetic dipole moment

$$\vec{m}$$

is forced toward the +X axis. Otherwise, the magnetization domain wall 120 magnetized the -Y axis with the magnetic dipole moment

$$\vec{m}$$

is forced toward the -X axis.

[76] Thus, the magnetic domain wall 120 magnetized along the +Y axis shifts toward the +X axis while the magnetic domain wall 120 magnetized along the -Y axis shifts toward the -X axis.

[77] If the adjacent magnetic domain walls 120a and 120c are contrary to each other in magnetization direction, the unit magnetic domains 110b and 110c may be shrunk down due to the shift of those magnetic domain walls and finally disappeared. Thereby, data stored in the magnetic domains 110 may be lost.

[78] Meanwhile, if the magnetic domain walls 120 are aligned in the same magnetization direction, those magnetic domain walls can shift to the same course. As it is possible to change locations of the magnetic domain walls 120 without losing data of the magnetic

domains 110, the MFD-driven MDWM memory device is suitable for storage.

[79] In the structure that the magnetic domain 110 includes the plural unit magnetic domains 110b and 110c, the magnetic domain wall 120 adjacent to the magnetic domain 110 shifts to result in migration of the magnetic domain 110 naturally. Thus, it prevents loss of data stored in the magnetic domains 110.

[80] For instance, if the adjacent unit magnetic domains 110b and 110c are aligned in the same magnetization direction, there would be no magnetic domain wall between them. In this case, the shift of the magnetic domain walls 120a and 120c placed at both sides of the unit magnetic domains 110b and 110c may cause the unit magnetic domains 110b and 110c to migrate (or move).

[81] The data storage pattern 100 may be further comprised of a temporary data storage region in addition to a magnetized region. The magnetized region may include the magnetic domains 110 and the magnetic domain walls 120, storing data or information. The temporary data storage region may be provided for provisionally reserve data that is stored in the magnetized region. The temporary data storage region is modified or altered by a driving method of the memory device according to the present invention.

[82] According to a modified embodiment of the present invention, it is permissible to provide another feature, not restrictive to the condition that the magnetization direction of the magnetic domain wall 120 is the same with the direction of the driving magnetic flux density, as long as the magnetic domain wall 120 is able to move by the driving magnetic flux density that unevenly applied thereto spatially.

[83] The magnetic flux density (or magnetic field)  $B$  and the magnetic field intensity  $H$  are relevant to each other as follows, so they may be defined in the same meaning.

[84]  $\vec{B} = \mu \vec{H}$ ,  $\mu$  is permeability.

[85] FIGs. 2 is view illustrating the shift of magnetic domain walls when the magnetic flux density is unevenly applied to the MFD-driven MDWM memory device of the present invention.

[86] Referring to FIG. 2(A), if the driving magnetic flux density  $B_y$  having a Y axis component is valued in positive and the gradient

$$\frac{\partial B_y}{\partial x}$$

of the driving magnetic flux density  $B_y$  is a positive, the magnetic domain wall 120a magnetized along the Y axis is able to shift toward the X axis along which the driving magnetic flux density  $B_y$  increases. According to this, the unit magnetic domains 110a and 110b disposed at both sides of the magnetic domain wall 120a move together therewith.

[87] On the other hand, if the driving magnetic flux density  $B_y$  having a Y axis

component is valued in positive but the gradient

$$\frac{\partial B_y}{\partial x}$$

of the driving magnetic flux density  $B_y$  is a negative, the magnetic domain wall 120a magnetized along the +Y axis is able to shift toward the -X axis along which the driving magnetic flux density  $B_y$  increases.

- [88] Further, if the driving magnetic flux density  $B_y$  having a Y axis component is valued in negative and the gradient

$$\frac{\partial B_y}{\partial x}$$

of the driving magnetic flux density  $B_y$  is a negative, the magnetic domain wall 120a magnetized along the +Y axis is able to shift toward the -X axis along which the driving magnetic flux density  $B_y$  decreases in absolute value.

- [89] If the driving magnetic flux density  $B_y$  having a Y axis component is valued in negative and the gradient

$$\frac{\partial B_y}{\partial x}$$

of the driving magnetic flux density  $B_y$  is a positive, the magnetic domain wall 120a magnetized along the +Y axis is able to shift toward the +X axis along which the driving magnetic flux density  $B_y$  decreases in absolute value.

- [90] The energy of the magnetic domain wall 120a is reduced as much as the driving magnetic flux density parallel with itself in magnetization direction becomes larger in absolute value, or as the driving magnetic flux density parallel with itself in magnetization direction becomes smaller in absolute value. Thus, the magnetic domain wall 120a shifts by the driving magnetic flux density that is unevenly applied toward a direction minimizing its own energy.

- [91] As the magnetic domain wall 120a can be stabilized between the adjacent magnetic domains 110a and 110b, it may need the minimum gradient

$$\left[ \frac{\partial B_y}{\partial x} \right]_{\min}$$

of the driving magnetic flux density  $B_y$  and the minimum intensity  $[B_y]_{\min}$  of the driving magnetic flux density.

- [92] When the magnetization direction of the magnetic domain 110a is parallel to an external magnetic flux density, the energy state can be stabilized. If the external magnetic flux density, i.e.,

$$\vec{B}$$

is larger than a predetermined critical magnetic flux density, the magnetization direction of the magnetic domain 110a may rotate along the direction of the external magnetic flux density. Thus, in order to prevent data disturbance by rotation along the magnetization direction, the intensity of the external magnetic flux density

$$\vec{B}$$

must be smaller than the critical magnetic flux density.

- [93] If the external magnetic flux density acts as the driving magnetic flux density for shifting the magnetic domain wall 120a, the magnetic domain 110a of the data storage pattern 100 rotate by the driving magnetic flux density  $B_y(x)$ . In this case, data recorded in the magnetic domain 110a would be lost. Thus, the intensity of the driving magnetic flux density  $B_y(x)$  is preferred to be over the minimum value for shifting the magnetic domain wall 120a and less than the maximum value for rotating the magnetic domain 110a.
- [94] The driving magnetic flux density  $B_y(x)$  may be periodically applied thereto in space. A spatial period may be  $n$  or  $1/n$  times of the length of the unit area ( $n$  is a positive integer). The gradient of the driving magnetic flux density  $B_y(x)$  varies by position. The driving magnetic flux density  $B_y(x)$  also varies by time or may be applied in the form of pulse.
- [95] Referring to FIG. 2(B), the magnetic domain walls and magnetic domains of the data storage pattern 100 have their initial locations. By applying the driving magnetic flux density thereto as shown in FIG. 2(A), the magnetic domain wall 120a and the magnetic domains, 110a and 110b, of FIG. 2(B), move to the locations shown in FIG. 2(C).
- [96] Distances and moving speed of the magnetic domain wall 120a and the magnetic domains 110a and 110b are dependent on material property of the data storage pattern 100, presence of a pinning region that will be described later, and a fashion and applying time of the driving magnetic flux density.
- [97] FIGs. 3 is view illustrating movement of magnetic domain walls when the driving magnetic flux density (shown in FIG. 3(A)) is unevenly applied to the MFD-driven MDWM memory device of the present invention. The initial location of the magnetic domain wall 120 shown in FIG. 3(B) is changed as shown in FIG. 3(C) by means of the first driving magnetic flux density  $B_{y1}(x)$  applied thereto between times  $t_1 \sim t_2$ . Applying the second driving magnetic flux density  $B_{y2}(x)$  thereto between times  $t_2 \sim t_3$ , the magnetic domain wall 120 of FIG. 3(C) shifts to the location as shown in FIG. 3(D).
- [98] Referring to FIG. 3(A), the spatially periodic driving magnetic flux density  $B_y(x)$  may be generated by a current flowing through a drive pattern (not shown). The drive

pattern is configured in a topological structure for generating the spatially periodic driving magnetic flux density  $By(x)$ . The spatially periodic driving magnetic flux density  $By(x)$  may be one or more in number. Between the times  $t1 \sim t2$ , the first driving magnetic flux density  $By_1(x)$  spatially shaped in a saw tooth may be applied to the data storage pattern 100. Additionally, between the times  $t2 \sim t3$ , the second driving magnetic flux density  $By_2(x)$  spatially shaped in a saw tooth may be applied to the data storage pattern 100. The first driving magnetic flux density  $By_1(x)$  may be different from the second driving magnetic flux density  $By_2(x)$  in waving shape.

[99] According to another modification by the present invention, the driving magnetic flux density  $By(x)$  is variable in shape, not restrictive to the shape of saw tooth.

[100] According to another modification by the present invention, it is able for the data storage pattern 100 to have pluralities of unit areas along the progress direction. In this case, the driving magnetic flux density  $By(x)$  operates with a spatial period as long as the length of the unit area, or integer times thereof, along the progress direction of the data storage pattern 100. Namely, the spatial period of the driving magnetic flux density  $By(x)$  may be one, two, three times of the length of the unit area.

[101] The first and second driving magnetic flux densities,  $By_1(x)$  and  $By_2(x)$ , may have their maximum and minimum values. The driving magnetic flux density  $By(x)$  may be valued in a positive or negative in accordance with a location of the gradient

$$\frac{\partial By}{\partial x}$$

thereof. A region with a positive value of

$$\frac{\partial By}{\partial x}$$

may be wider than a region with a negative value of

$$\frac{\partial By}{\partial x}.$$

[102] The regions with positive or negative values of

$$\frac{\partial By}{\partial x}$$

may be arranged in sequence.

[103] At the time  $t1$ , the magnetic domain wall 120 of the data storage pattern 100 may be conditioned in a stabilization state. Thus, the strong force may be needed to shift the magnetic domain wall 120. Since the force to the magnetic dipole moment

$$\vec{m}$$

of the magnetic domain wall 120 becomes stronger in proportion to a value of

$$\frac{\partial B_y}{\partial x},$$

it is preferred to form

$$\frac{\partial B_y}{\partial x}$$

in accordance with locations. For instance, the gradient

$$\frac{\partial B_y}{\partial x}$$

may be larger at the location of the magnetic domain wall 120 that is conditioned in the initial state of the time t1, than at another location.

[104] According to another modification by the present invention, the driving magnetic flux density  $B_y(x)$  may be composed of pluralities of driving magnetic flux densities  $B_{y_n}(x)$  ( $n$  may be larger than 1). Thus, the driving magnetic flux density  $B_y(x)$  can be composed by including the first and second driving magnetic flux densities,  $B_{y_1}(x)$  and  $B_{y_2}(x)$ , which are differently formed to each other. The first and second driving magnetic flux densities,  $B_{y_1}(x)$  and  $B_{y_2}(x)$ , can be applied to the data storage pattern 100 at the same time or different times. A current flowing through the drive pattern (not shown) generating the driving magnetic flux density  $B_y(x)$  may be fluctuated by time. Further, the current of the drive pattern may be supplied in the form of pulse.

[105] According to another modification by the present invention, the first and second driving magnetic flux densities,  $B_{y_1}(x)$  and  $B_{y_2}(x)$ , may be same or different from each other in direction.

[106] Referring to FIG. 3(B), the magnetic domains 110 of the data storage pattern 100 may be magnetized to the -X axis, while the magnetic domain walls 120 may be magnetized to the +Y axis.

[107] There is shown the shift with the magnetic domain wall 120 of the data storage pattern 100 when the first driving magnetic flux density  $B_{y_1}(x)$  is applied to the data storage pattern 100 between the times t1 ~ t2. After applying the first driving magnetic flux density  $B_{y_1}(x)$ , the magnetic domain wall 120 magnetized along the Y axis can shift toward the +X axis in a predetermined rate by a gradient

$$\frac{\partial B_{y_1}(x)}{\partial x}$$

of the first driving magnetic flux density  $B_{y_1}(x)$ .

[108] During this, the predetermined shift rate may be dependent on the intensity of the

first driving magnetic flux density  $By_1(x)$  and a sign of the gradient of the first driving magnetic flux density  $By_1(x)$ . The predetermined shift rate may be affected from a quantity of saturated magnetization of the data storage pattern 100, physical property such as magnetic anisotropy energy, a thickness and width of the data storage pattern 100, and the pinning energy to be described later.

[109] For example, at the time  $t1$ , as the gradient

$$\frac{\partial By_1(x)}{\partial x}$$

of the first driving magnetic flux density  $By_1(x)$  is valued in positive on the location of the magnetic domain wall 120, the magnetic domain wall 120 can shift to the +X axis.

[110] According to another modification, the gradient

$$\frac{\partial By_1(x)}{\partial x}$$

is variable by locations.

[111] At the time  $t1$ , the magnetic domain wall 120 can be placed in the area having a positive value of the gradient

$$\frac{\partial By_1(x)}{\partial x}$$

of the first magnetic flux density  $By_1(x)$ . And, at the initial time  $t1$ , the gradient

$$\frac{\partial By_1(x)}{\partial x}$$

of the first magnetic flux density  $By_1(x)$  may be conditioned over the critical value

$$\left[ \frac{\partial By_1}{\partial x} \right]_{\min}$$

on the location of the magnetic domain wall 120. According to this, the magnetic domain wall 120 is able to shift toward +X axis along time.

[112] At the location corresponding to the maximum value of the first magnetic flux density  $By_1(x)$ , the energy of the magnetic domain wall 120 may be conditioned in the stabilization state. Therefore, the magnetic domain wall 120 stops shifting at the location where the first magnetic flux density  $By_1(x)$  reaches the maximum value or where the gradient

$$\frac{\partial B_{y_1}(x)}{\partial x}$$

of the first magnetic flux density  $B_{y_1}(x)$  changes in sign. The location corresponding to the maximum value of the first magnetic flux density  $B_{y_1}(x)$  may be apart from the initial location of the magnetic domain wall 120 by a distance  $d1$ . But, if the gradient

$$\frac{\partial B_{y_1}(x)}{\partial x}$$

is locally conditioned in negative, the magnetic domain wall 120 may be out of the stabilization state of energy. Then, the magnetic domain wall 120 may shift over the local area with a negative

$$\frac{\partial B_{y_1}(x)}{\partial x}$$

[113] FIG. 3(C) illustrates a feature of shifting the magnetic domain wall 120 of the data storage pattern 100 when the second magnetic flux density  $B_{y_2}(x)$  is applied to the data storage pattern 100 between the times  $t2 \sim t3$ . After the magnetic domain wall 120 has shifted by  $d1$  along the +X axis by the first magnetic flux density  $B_{y_1}(x)$ , the second magnetic flux density  $B_{y_2}(x)$  may be applied to the data storage pattern 100 at the time  $t2$ .

[114] According to another modification by the present invention, before the magnetic domain wall 120 shifts to the location of the maximum

$$\frac{\partial B_{y_1}(x)}{\partial x}$$

by the first magnetic flux density  $B_{y_1}(x)$ , the second magnetic flux density  $B_{y_2}(x)$  can be applied to the data storage pattern 100. A time gap of applying between the first and second magnetic flux densities  $B_{y_1}(x)$  and  $B_{y_2}(x)$  is variable by conditions.

[115] The second magnetic flux density  $B_{y_2}(x)$  may have the maximum and minimum values. The gradient

$$\frac{\partial B_{y_2}(x)}{\partial x}$$

of the second magnetic flux density  $B_{y_2}(x)$  may be conditioned in positive or negative. The areas with positive and negative values of

$$\frac{\partial B_{y_2}(x)}{\partial x}$$

can be arranged in sequence.

[116] According an embodiment by the present invention, the location corresponding to the maximum value of the second magnetic flux density  $B_{y_2}(x)$  may be identical to the location of the magnetic domain wall 120 of the data storage pattern 100 at the initial time t1. Thus, it is able to shift the magnetic domain wall 120 by the unit area through applying the first and second magnetic flux densities  $B_{y_1}(x)$  and  $B_{y_2}(x)$  to the data storage pattern 100.

[117] According another embodiment by the present invention, the location corresponding to the maximum value of the second magnetic flux density  $B_{y_2}(x)$  may disagree to the location of the magnetic domain wall 120 of the data storage pattern 100 at the initial time t1. For the purpose of solving the positional disagreement, the data storage pattern 100 may include the pinning region to be described later.

[118] At the time t2, the magnetic domain wall 120 may be disposed in an area where the gradient

$$\frac{\partial B_{y_2}(x)}{\partial x}$$

of the second magnetic flux density  $B_{y_2}(x)$  is conditioned in positive. Thereby, the magnetic domain wall 120 is able to shift to the location with the maximum value of the second magnetic flux density  $B_{y_2}(x)$ .

[119] FIG. 3(D) illustrates a location of the magnetic domain wall 120 at the time t3 after a predetermined time since the second magnetic flux density  $B_{y_2}(x)$  has been applied to the data storage pattern 100. The magnetic domain wall 120 may be conditioned in the same with the previous state when the first magnetic flux density  $B_{y_1}(x)$  is applied thereto at the time t1.

[120] Through the procedure of FIGs. 3(B) through 3(D), the magnetic domains of the data storage pattern 100 can be moved by the range of unit cell in location.

[121] The driving magnetic flux density described above includes all of other types shifted by means of

$$\frac{\partial B_{y_1}}{\partial x}$$

, not restrictive to the aforementioned. A method of forming

$$\frac{\partial B_{y_1}}{\partial x}$$

will be described later.

[122] While the feature shown in FIGs. 3(A) through 3(D) are exemplified about the case of shifting the magnetic domain wall 120 to right, it is also permissible to make the magnetic domain wall 120 shift to left in accordance with the shape of the driving magnetic flux density  $B_y(x)$ .

[123] FIGs. 4 and 5 are schematic views illustrating magnetization directions of the magnetic domain walls and magnetic domains in the MFD-driven MDWM memory device of the present invention.

[124] Referring to FIG. 4, the data storage pattern 100 is arranged along the X axis. The magnetic domains 110 are magnetized toward the +Z or -Z axis. And, the magnetic domain walls 120 are magnetized to the +Y axis.

[125] If the driving magnetic flux density

[126] 
$$B_y \neq 0, \frac{\partial B_y}{\partial x} \neq 0$$

[127] is applied to the data storage pattern 100, it is able for the magnetic domain wall 120 to shift toward another location.

[128] Referring to FIG. 5, the data storage pattern 100 is disposed along the X axis. The magnetic domains 110 can be magnetized to the +X or -X axis. And, the magnetic domain walls 120 are magnetized to the +Z axis. If the driving magnetic flux density

[129] 
$$B_x \neq 0, \frac{\partial B_x}{\partial x} \neq 0$$

[130] is applied to the data storage pattern 100, it is able for the magnetic domain wall 120 to shift toward another location.

[131] According to another modification by the present invention, the magnetic domain wall 120 may be vertical to the magnetic domain 110 in magnetization direction. The magnetization directions of the magnetic domain 110 and the magnetic domain wall 120 can be transformed anytime as long as they are vertical to each other. But, the magnetic domain walls 120 may be magnetized unilaterally.

[132] FIGs. 6 and 7 are schematic views illustrating a method of forming magnetic domain walls oriented in the same magnetization direction in the MDWM memory device of the present invention.

[133] In the MDWM memory device according to an embodiment of the present invention, the magnetic domain walls 120a and 120b of the data storage pattern 100 are aligned to the same magnetization direction, shifting to left or right together. Unless the magnetic domain walls 120a and 120b are aligned to the same magnetization direction, it may

occur that the magnetic domain walls cannot shift to a unilateral direction. Thus, there must be an additional step for aligning the magnetic domain walls 120a and 120b to the same magnetization direction.

- [134] Referring to FIG. 6, the writing structure (not shown) applies a strong magnetic flux density  $-B_x$  to the magnetic domain 110b of the center of the data storage pattern 100, the magnetic domain 110b can be magnetized toward the  $-X$  axis. In this case, the magnetic domain walls 120a and 120b may be formed contrary to each other in magnetization direction. Thus, the magnetic domain walls 120a and 120b may be set to the magnetization direction along the  $+Y$  or  $-Y$  axis.
- [135] Referring to FIG. 7, the magnetic flux density ( $-B_x$ ) directed to the  $-X$  axis is applied to the magnetic domain 110b of the data storage pattern 100 so as to make the magnetic domain 110b aligned to the  $-X$  axis. At the same time, if the driving magnetic flux density (or magnetic domain wall aligning magnetic flux density)  $B_y$  directed to the  $+Y$  axis is applied thereto, the magnetic domain walls 120a and 120b adjacent to the magnetic domain 110b may be magnetized toward the  $+Y$  axis.
- [136] For instance, the magnetic domain wall 120a, which is generated between the magnetic domain 110a magnetized to the  $+X$  axis and the magnetic domain 110b magnetized to the  $-X$  axis, may be magnetized to the  $+Y$  or  $-Y$  axis. In this case, determining the magnetization direction of the magnetic domain wall 120a toward the  $+Y$  or  $-Y$  axis may be minutely dependent on the initial conditions. Thereby, it is able to align the magnetic domain wall 120a toward the  $+Y$  axis by applying the driving magnetic flux density  $B_y$  of the  $+Y$  axis from external. But, the intensity of the driving magnetic flux density  $B_y$  of the  $+Y$  axis for aligning the magnetic domain wall 120a to the  $+Y$  axis may be less than that of the magnetic flux density directed to the  $\pm X$  axis (i.e.,  $+X$  or  $-X$  axis) for aligning the magnetic domains to the  $\pm X$  axis.
- [137] FIGs. 8 through 10 are schematic views illustrating a procedure for aligning magnetic domain walls in the MFD-driven MDWM memory device of the present invention.
- [138] First, the data storage pattern 100 is disposed on a substrate 10. The writing structure 200 and the reproducing structure 300 may be placed around the data storage pattern 100. Through a procedure (writing or programming) for generating the magnetic domains 110 of the data storage pattern 100, the magnetic domain walls 120 can be aligned to a uniform direction. For instance, the magnetic domains 110 of the data storage pattern 100 can be magnetized along the  $\pm X$  axis. In this case, the magnetization direction of the magnetic domains 110 is determined by the magnetic flux density that is generated from the writing structure and directed to the  $\pm X$  axis. The magnetic flux density directed to  $\pm X$  axis is generated by applying a current to the writing structure 200 intersecting the data storage pattern 100. The writing structure 200 may include a structure such as a general hard disk writing head.

- [139] Additionally, a magnetic flux focusing material 202 may be interposed between the writing structure 200 and the data storage pattern 100, concentrating the magnetic flux density generated from the writing structure 200. The magnetic flux focusing material 202 may be made of a ferromagnetic material.
- [140] Referring to FIG. 8, a magnetic domain wall aligning structure (hereinafter, MDW-aligning structure) 210 may be disposed around the magnetic domain wall 120. The MDW-aligning structure 210 operates to align the magnetic domain wall 120 between the magnetic domains 110.
- [141] The MDW-aligning structure 210 may include a conductive pattern. The MDW-aligning structure 210 may be placed around the writing structure 200. A shape of the conductive pattern is variable by those skilled in the art under the condition with a component of the magnetic flux density directed to the  $\pm Y$  axis.
- [142] As shown in FIG. 8, the memory device according to the present invention can be comprised of the writing and reproducing structures 200 and 300. The writing structure 200 is used as means for writing (or recording) data into the magnetic domains 110 of the data storage pattern 100. The writing structure 200 may include a conductive line, coil, or ferromagnetic materials in order to enhance the flux density.
- [143] The reproducing structure 300 is used as means for reading data from the magnetic domains 110 of the data storage pattern 100, according to a magnetization direction. The reproducing structure 300 may include a sensor 310 for detecting a magnetization direction of the magnetic domain 110. The sensor 310 is electrically connected to the reproducing structure 300. The sensor 310 may be a tunneling magneto-resistance sensor, a giant magneto-resistance sensor, or an anisotropic magneto-resistance sensor.
- [144] Referring to FIG. 9, for the purpose of aligning the magnetic domain wall 120 toward the  $+Y$  axis, the MDW-aligning structure 210 may be disposed around the magnetic domain wall 120 in number of at least one or more. The MDW-aligning structure 210 may be formed of a permanent magnet. Namely, a magnetic force line by the permanent magnet is able to generate the magnetic flux density of the  $\pm Y$  axis.
- [145] According to another modification by the present invention, it is permissible to apply an externally-biased magnetic flux density to the MFD-driven MDWM memory device so as to generate the magnetic flux density of the  $\pm Y$  axis for aligning the magnetic domain walls 120.
- [146] Referring to FIG. 10, the MDW-aligning structure 210 is able to apply the externally-biased magnetic flux density to the data storage pattern 100. The MDW-aligning structure 210 may be made of a permanent magnet or electromagnet.
- [147] According to another modification by the present invention, the data storage pattern 100 may be configured in unidirectional anisotropy in order to align the magnetic domain walls 120 in a specific magnetization direction. Here, the unidirectional

anisotropy means the property capable of aligning the magnetic domain walls to a predefined direction of magnetization. In practice, a material with the uniaxial anisotropy may be included in the data storage pattern 100 or the MDW-aligning structure 210. If the MDW-aligning structure 210 contains the unidirectional anisotropy material, a plurality of the MDW-aligning structure is arranged in parallel on the data storage pattern 100.

[148] According to another modification by the present invention, the MDW-aligning structure 210 is periodically placed along the data storage pattern 100.

[149] According to another embodiment by the present invention, the magnetic domain walls can be aligned to a unilateral magnetization direction by means of an exchange bias with an anti-ferromagnetic material. The exchange bias is an effect forming a magnetic hysteresis curve asymmetrical to a magnetic field by means of an anti-ferromagnetic material in a bi-layer structure of ferromagnetic and anti-ferromagnetic materials. The anti-ferromagnetic material acts to grant unidirectional anisotropy energy to the ferromagnetic material. Therefore, if the data storage pattern 100 includes a ferromagnetic material and the MDW-aligning structure 210 includes an anti-ferromagnetic material, it is able to align the magnetic domain walls 120 in a unidirectional (or unilateral) magnetization direction.

[150] As an example, the MDW-aligning structures 210 may be disposed around the data storage pattern 100. Each MDW-aligning structure may include an anti-ferromagnetic material. Thereby, the data storage pattern 100 and the MDW-aligning structure 210 may be comprised of a bi-layer structure of ferromagnetic and anti-ferromagnetic materials. The anti-ferromagnetic materials are alloys or oxides of iron (Fe), manganese (Mn), cobalt (Co), nickel (Ni), platinum (Pt), iridium (Ir), such as FeMn, IrMn, PtMn, CoO, or NiO. The anti-ferromagnetic material may be made by a compound or alloy of the aforementioned materials.

[151] FIGs. 11 through 13 are schematic views illustrating features of pinning in the MFD-driven MDWM memory device of the present invention.

[152] Pinning means methodology or means for preventing the magnetic domain wall 120 from miss-shifting or over-shifting. For instance, the pinning operation makes the magnetic domain wall 120 stabilized with the least energy localized at a predetermined location. The magnetic domain wall 120 of the data storage pattern 100 is easy to move due to interaction with its peripheral material or magnetic flux density. To assure the reliability of the data storage pattern 100, the magnetic domain wall 120 must not shift to another location inadvertently as long as there is no external force thereto. For that reason, the data storage pattern 100 may be comprised of a pinning region 130a for blocking an inadvertent shift of the magnetic domain wall 120. But, the pinning region 130a may be fixed physically, different from the magnetic domain 110 and the

magnetic domain wall 120. The pinning region 130a may be formed by the inherent property of the data storage pattern 100, or disposed on the data storage pattern 100 by a pinning structure that will be described later.

[153] Referring to FIG. 11, a width  $w$  of the data storage pattern 100 is locally variable on the pinning region 130a.

[154] For instance, within the pinning region 130a, the width of the data storage pattern 100 may be narrower or wider than a width of another area. In this case, if the magnetic domain wall 120 is disposed in the pinning region 130a, it is possible to stabilize the magnetic domain wall by reducing the total energy of the data storage pattern 100.

[155] According to another modification by the present invention, the effect of pinning is generated by diversifying curvature radii of the data storage pattern 100. If the data storage pattern 100 is formed in a serpentine shape, a part with a smaller curvature radius can be used for the pinning region 130a.

[156] A spatial period of the pinning region 130a may be relevant to the spatial period of the magnetic domain wall 120 in integer times. For instance, one or two members of the magnetic domain walls 120 can be disposed between two pinning regions 130a successively arranged. According to a modification by the present invention, one or two pinning regions 130a may be placed between two magnetic domain walls 120. It is preferred to dispose one magnetic domain wall in the pinning region 130a.

[157] Referring to FIG. 12, the thickness  $t$  of the data storage pattern 100 is locally variable lengthways. Thereby, an area with a locally different thickness along the data storage pattern 100 can be used for the pinning region 130a. For instance, in the pinning region 130a, the data storage pattern 100 becomes smaller or larger in thickness. In this case, if the magnetic domain wall 120 is disposed in the pinning region 130a, it takes an effect of reducing the total energy of the data storage pattern 100 and hence stabilizes the magnetic domain walls 120.

[158] According another modification by the present invention, it is able to form the pinning region 130a by locally varying the magnetic anisotropy energy of the data storage pattern 100. For instance, impurities may be locally added to the data storage pattern 100. The impurities are injected therein by means of an ion implantation or diffusion process. It is available for the impurities to be oxygen, fluorine, metal, or transition metal, not restrictive to the material forming the data storage pattern 100.

[159] According to another modification, it is also permissible to locally form defects or voids on the data storage pattern 100 by means of high ion energy. Then, the defects or voids can be used for the pinning region 130a.

[160] According to another embodiment, for the pinning region 130a on the data storage pattern 100, there are variously provided local oxidation, formation of voids, or change

of material. For instance, the oxidation is carried out by plasma oxidation, or thermal oxidation.

- [161] According to another modification by the present invention, it is able to form the pinning region 130a by means of interlayer exchange coupling energy between the data storage pattern 100 and other material. The interlayer exchange coupling action is an effect resulting from a triple layer structure of ferromagnetic, nonmagnetic, ferromagnetic materials in order, aligning magnetization direction of the two ferromagnetic layers to be parallel or anti-parallel with each other in accordance with a thickness of the nonmagnetic layer. The nonmagnetic layer may be formed of a 3d, 4d, or 5d transition metal (e.g., copper: Cu, ruthenium: Ru, chrome: Cr, gold: Au, etc.), a semiconductor (silicon: Si or germanium: Ge), gallium arsenide (GaAs), or a compound of them.
- [162] As an example, pinning structures 140 can be provided around the data storage pattern 100. Thus, the data storage pattern 100 and the pinning structure 140 may include the triple layer structure of ferromagnetic, nonmagnetic, ferromagnetic materials in order. The pinning structure 140 may include double layers of nonmagnetic and ferromagnetic materials. Thus, the pinning region 130a may be formed of the triple layer structure with ferromagnetic, nonmagnetic, ferromagnetic materials in order.
- [163] According to another modification by the present invention, it is able to form the pinning region 130a by means of an exchange bias between the data storage pattern 100 and the anti-ferromagnetic layer. The exchange bias is an effect forming a magnetic hysteresis curve asymmetrical to a magnetic flux density by means of an anti-ferromagnetic material in a double layer structure of ferromagnetic and anti-ferromagnetic materials. The anti-ferromagnetic material acts to grant unidirectional anisotropy energy to the ferromagnetic material. For instance, the data storage pattern 100 and the pinning structure 140 may include a double layer structure of ferromagnetic and anti-ferromagnetic materials. Therefore, the data storage pattern 100 may be comprised of a ferromagnetic material and the pinning structure 140 may be comprised of an anti-ferromagnetic material. The pinning region 130a may be formed in a double layer structure of ferromagnetic and anti-ferromagnetic materials.
- [164] According to another modification by the present invention, it is able to form the pinning region 130a by disposing spring magnets with high coercive force around the data storage pattern 100, locally minimizing energy at the location of the magnetic domain wall 120 of the data storage pattern 100. The spring magnet is formed in a magnetic structure with double or multi-level films of soft and hard magnetic materials. In the spring magnet, it is possible to make the magnetization direction of the soft magnetic material intend to be parallel or anti-parallel to the magnetization

direction of the hard magnetic material. Since it is difficult for the magnetization direction of the hard magnetic material with high coercive force to change, the hard magnetic material may be regarded as fixed to itself in magnetization direction. As the soft magnetic material is affected from the hard magnetic material in magnetization direction, it is able to selectively follow the intended magnetization direction. For instance, the data storage pattern 100 includes a soft magnetic material. The pinning structure 140 including a hard magnetic material may be disposed over or under the data storage pattern 100. Then, it is able to select a magnetization direction of the magnetic domain wall 120 in the pinning structure 130a of the data storage pattern 100. The pinning structure 140 and the data storage pattern 100 may be comprised of double or multi-level films of soft and hard magnetic materials.

- [165] Referring to FIG. 13, the pinning structure 140 can be disposed around the data storage pattern 100 in the space ranged from 0.1 nm to 1000 nm. The pinning structure 140 may be formed of a soft magnetic material.
- [166] The data storage pattern 100 conducts magnetic dipole interaction with the pinning structure 140 using a soft magnetic material. The pinning structure 140 with a soft magnetic material is able to form the pinning region 130a for confining the magnetic domain wall 120. The soft magnetic material may be a ferromagnetic material that is easily saturated by an external magnetic flux density. The soft magnetic materials may include 3d transition metals or their alloys, e.g., Fe, Co, Ni, FeNi, CoFe, CoFeSi, and CoFeSiB. A width and length of the pinning structure 140 with such a soft material may be ranged from 1 nm to 1000 nm. The pinning structure 140 is variable in shape, not restrictive to a parallelepipedon.
- [167] FIGs. 14 through 16 are schematic views illustrating structures of the data storage patterns in the MFD-driven MDWM memory device of the present invention.
- [168] Referring to FIG. 14, the data storage pattern 100 may be shaped in a strip line. The data storage pattern 100 may be comprised of plural magnetic domains 110 and at least one magnetic domain wall 120. The data storage pattern 100 may be further comprised of the pinning region 130a.
- [169] The data storage pattern 100 may include at least one of a ferromagnetic material layer, a ferromagnetic alloy layer, and a ferrimagnetic material layer. The data storage pattern 100 may further include at least one of nonmagnetic and anti-ferromagnetic material layers. Thus it is available for the data storage pattern 100 to be formed in a single, double, or triple layer structure, or combinations thereof. The thickness or width of the data storage pattern 100 ranges from 1 nm to 1000 nm.
- [170] The ferromagnetic material is at least one selected from the 3d, 4d, and 5d transition metals such as Fe, Co, and Ni, alloys of the transition metals, the rare earth metals, and alloys of the rare earth metals.

- [171] Referring to FIG. 14, the data storage pattern 100 may be formed in a double layer structure of the bottom and top layers 400 and 102. The bottom layer 400 may be made of a ferromagnetic, nonmagnetic, or anti-ferromagnetic material. The top layer 102 may be made of a ferromagnetic material. The data storage pattern 100 can be formed by sequentially patterning the top and bottom layers 102 and 400 through photolithography and etching processes.
- [172] According to another modification by the present invention, it is permissible to differentiate the top and bottom layers 102 and 400 from each other in pattern. In other words, the bottom layer 400 may not be shaped in the patterning process (i.e., the photolithography and etching processes). Further, according to another embodiment, it is possible to change materials between the top and bottom layers 102 and 400 with each other.
- [173] Referring to FIG. 15, the data storage pattern 100 may be formed in a triple layer structure of first, second, and third layers 400, 104, and 410. The second layer 104 may be made of a ferromagnetic material. The first and third layers 400 and 410 may be made of ferromagnetic, nonmagnetic, or anti-ferromagnetic materials.
- [174] Referring to FIG. 16, the data storage pattern 100 may be formed in a triple layer structure of first, second, and third layers 106, 400, and 108. The first and third layers 106 and 108 may be made of ferromagnetic materials and the second layer 400 may be made of a nonmagnetic or anti-ferromagnetic material. The first and third layers 106 and 108 are relative with anti-parallel magnetization direction to each other.
- [175] From the aforementioned description, it can be seen that the structure of the data storage pattern 100 may be further modified or altered in various types, not to restrictive just to the single, double, or triple layer structure.
- [176] FIGs. 17 through 20 are schematic views illustrating shapes of the data storage patterns in the MFD-driven MDWM memory device of the present invention. Referring to FIG. 17, the data storage pattern 100 is comprised of the plural magnetic domains 110 and the magnetic domain wall 120, which may be formed in a serpentine shape. The serpentine shape is helpful to the pinning function. The serpentine shape may be periodical along the progress direction of the data storage pattern 100. The magnetic domain wall 120 can be disposed at a location with the smallest curvature radius of the serpentine.
- [177] Referring to FIG. 18, the data storage pattern 100 may be divided into linear and curved regions. The magnetic domain 110 may be disposed in the linear region while the magnetic domain wall 120 may be disposed in the curved region. The curved regions can be used for the pinning function.
- [178] According to another modification by the present invention, a shape of the data storage pattern 100 may not be limited to the aforementioned, but is variable by those

artisans of this art. A width and thickness of the data storage pattern 100 may be locally differentiated in order to providing the pinning function.

[179] Referring to FIG. 19, the data storage pattern 100 including the magnetic domain wall 120 and the magnetic domain 110 may be shaped in an open loop. The data storage pattern 100 can be also arranged on a vertical plane, not restricted to that it is laid on the same horizontal plane.

[180] Referring to FIG. 20, the data storage pattern 100 may be shaped in a closed loop. This closed loop is variable in free styles.

[181] FIGs. 21 and 22 are schematic views illustrating shielding structures of the MFD-driven MDWM memory device of the present invention.

[182] Referring to FIG. 21, the data storage patterns 100 can be arranged in three dimensions. First and second data storage patterns 100c and 100d, at the bottom and top sides, may easily interact to each other. For the purpose of lessening the interaction between the first and second data storage patterns 100c and 100d, the shielding structure 500 may be interposed between the first and second data storage patterns 100c and 100d.

[183] In addition, around the first data storage pattern 100c, a first drive pattern (not shown) may be provided to generate the driving magnetic flux density  $B_y$  for shifting the magnetic domain wall 120 of the first data storage pattern 100c. The driving magnetic flux density  $B_y$  generated by the first drive pattern is able to affect the second data storage pattern 100d adjacent thereto, so that the shielding structure 500 is interposed between the data storage patterns 100c and 100d.

[184] The shielding structure 500 may be formed by including at least one of ferromagnetic and ferrimagnetic materials.

[185] Referring to FIG. 22, the data storage patterns 100 may be arranged in two dimensions.

[186] A first data storage pattern 100e and a first drive pattern for activating the first data storage pattern 100e are able to affect a second data storage pattern 100f adjacent to them. For that reason, the shielding structure 500 may be interposed between the data storage patterns 100e and 100f.

[187] According to another modification by the present invention, the feature of the shielding structure may be transformed in various forms by those skilled in the art.

[188] FIGs. 23 and 24 are schematic views illustrating drive patterns of the MFD-driven MDWM memory device of the present invention.

[189] Referring to FIG. 23, the data storage pattern 100, which includes the plural magnetic domains 110 and at least one of the magnetic domain walls 120, is progressing along the X axis. At least one drive pattern may be disposed around the data storage pattern 100. The drive pattern 700 may be configured to apply the magnetic flux density  $B_y$ .

- riodically and unevenly to the data storage pattern 100.
- [190] For the periodical and uneven magnetic flux density, the drive pattern 700 may be formed in the optimum condition by computer simulation, theoretical evaluation, or experimental results.
- [191] An interval  $h$  between the drive pattern 700 and the data storage pattern 100 is variable in accordance with a location of the data storage pattern 100. A thickness  $t$  of the drive pattern 700 is variable according to a location thereof. A width  $w$  of the drive pattern 700 is also variable by a location thereof. An angle  $\varphi$  between the progress direction of the data storage pattern 100 and a progress direction of the drive pattern 700 is variable in accordance with a distance from a predetermined one of the magnetic domain walls 120 or a location of the drive pattern 700.
- [192] The drive pattern 700 may be disposed by obliquely intersecting the data storage pattern 100. The drive pattern 700 may be also placed at a side of the data storage pattern 100.
- [193] The drive pattern 700 may be formed of a conductive material. The conductive material may be a semiconductor, a conductor, or a metallic compound. The conductor may be copper (Cu), gold (Au), silver (Ag), aluminum (Al), tungsten (W), etc. The drive pattern 700 may be comprised of a plural layer structure having pluralities of conductive layers that are different to each other in electrical conductivity. Thus, there is a difference in current density by a location of the drive pattern 700.
- [194] The drive pattern 700 is configured to apply the periodically uneven magnetic flux density to the data storage pattern. A topological shape of the drive pattern 700 can be implemented by means of computer simulation.
- [195] According to another modification by the present invention with reference to FIG. 24, the drive pattern 700 may not be restrictive to the aforementioned in width and thickness. Rather, the drive pattern 700 is spatial-periodically variable in width, thickness, interval from the load storage pattern. For instance, the drive pattern 700 extends along the progress direction of the data storage pattern 100 in a serpentine shape. The drive pattern 700 may be disposed to generate the periodically uneven magnetic flux density.
- [196] The drive pattern 700 is provided in number of at least one in order to generate the driving magnetic flux density  $B_y(x)$ . Namely, the drive pattern 700 may be provided in plurality so as to form pluralities of the driving magnetic flux densities. The drive patterns 700 may include first and second drive patterns 710 and 720. The driving magnetic flux densities may be generated by flowing current through the drive patterns 700 at the same time or at a time. The current flowing through the drive pattern 700 may vary along time and be applied in a form of pulse.
- [197] FIGs. 25 and 26 are schematic views illustrating patterns of soft magnetic material in

the MFD-driven MDWM memory device of the present invention.

- [198] To vary a spatial pattern of the driving magnetic flux density by the drive pattern 700, a soft magnetic pattern 600 may be interposed between the drive pattern 700 and the data storage pattern 100.
- [199] Referring to FIG. 25, the data storage pattern 100 including the plural magnetic domains 110 and at least one of the magnetic domain walls 120 extends along the X axis. The data storage pattern 100 and the drive pattern 700 are shaped in strip lines, extending toward the X axis.
- [200] If a current flows through the drive pattern 700 extending along the X axis, the current makes the driving magnetic flux density induced. If the current steadily flows through the drive pattern 700, the driving magnetic flux density generated under the drive pattern 700 may be dependent upon a width of the drive pattern 700. Therefore, the width of the drive pattern 700 may be changed periodically so as to form the spatially periodic driving magnetic flux density.
- [201] Continued to FIG. 25, the periodic variation on the width of the drive pattern 700 along the X axis is able to form the uneven driving magnetic flux density.
- [202] The Y axis componential gradient of the driving magnetic flux density contributes to shifting the magnetic domain wall 120 of the data storage pattern 100. In this case, for the purpose of changing the Y axis component of the driving magnetic flux density by location, the soft magnetic pattern 600 may be placed between the data storage pattern 100 and the drive pattern 700. The soft magnetic pattern 600 is able to conduct a function of magnetic lens. Thereby, it is able to locally increase or decrease the Y axis component of the driving magnetic flux density. The soft magnetic pattern 600 is variable in topological structure. The permeability of the soft magnetic pattern 600 is also variable by locations.
- [203] The soft magnetic pattern 600 may be formed of a ferromagnetic material that is easily saturated by an external magnetic flux density. For example, the soft magnetic pattern 600 may include at least one selected from the 3d transition metals or alloys of them. Namely, the soft magnetic pattern 600 may be formed by including Fe, Co, Ni, FeNi, CoFe, CoFeSi, or CoFeSiB. A width of the soft magnetic pattern 600 may be ranged from 1 nm to 1000 nm. The soft magnetic pattern 600 may be variously shaped as like a triangle, tetragon, and so on, not restrictive to a parallelopipedon.
- [204] The soft magnetic pattern 600 may be configured to have magnetic anisotropy toward an arbitrary direction. And, the soft magnetic pattern 600 may be formed in a single layer structure of ferromagnetic material, a double layer structure of ferromagnetic and anti-ferromagnetic materials, a triple layer structure of ferromagnetic, nonmagnetic, and ferromagnetic materials in order, or a structure of first and second ferromagnetic layers. The structure of the soft magnetic pattern 600 may be variously

formed by those skilled in the art. The soft magnetic pattern 600 may be placed at the left side or right side of the data storage pattern 100.

- [205] The soft magnetic pattern 600 is able to conduct a function for setting the pinning region shown in FIG. 13. For instance, the soft magnetic pattern 600 is operable in magnetic dipole interaction with the magnetic domain walls 120 therearound. Thereby, the soft magnetic pattern 600 acts as the pinning structure 140.
- [206] To form a plurality of the driving magnetic flux density, the drive pattern 700 may be provided in plurality. Between the plural drive patterns 700 may be interposed an insulation film (not shown). For example, the drive pattern 700 may be composed of first and second drive patterns 710 and 720. And, the soft magnetic pattern 600 may be comprised of first and second soft magnetic patterns 610 and 620.
- [207] As illustrated in FIG. 25, the first and second drive patterns 710 and 720 are arranged on the data storage pattern 100 in sequence. Between the data storage pattern 100 and the first drive pattern 710 is interposed the first soft magnetic pattern 610. Between the first drive pattern 710 and the second drive pattern 720 is interposed the second soft magnetic pattern 620.
- [208] The first driving magnetic flux density  $By_1(x)$  is formed by applying a forward current (to the X axis) to the first drive pattern 710. And, the second driving magnetic flux density  $By_2(x)$  is formed by applying a forward current to the second drive pattern 720. If a reverse current (to the - X axis) is applied to the first drive pattern 710, a third driving magnetic flux density  $By_3(x)$  is generated therefrom. If a reverse current (to the - X axis) is applied to the second drive pattern 720, a fourth driving magnetic flux density  $By_4(x)$  is generated therefrom. By combining such driving magnetic flux densities  $By_1(x) \sim By_n(x)$ , it is able to shift the magnetic domain wall 120 to right or left.
- [209] Now referring to FIG. 26, the data storage pattern 100, which includes the plural magnetic domains 110 and at least one of the magnetic domain walls 120, is extending along the X axis. At least one drive pattern may be disposed around the data storage pattern 100. The drive pattern 700 may be configured to apply the magnetic flux density periodically and unevenly to the data storage pattern 100. For example, the drive pattern 700 may be comprised of first and second drive patterns 701 and 702 which are disposed over the data storage pattern 100, and third and fourth drive patterns 703 and 704 which are disposed under the data storage pattern 100. The drive patterns 710 ~ 704 obliquely intersect the data storage pattern 100, periodically disposed along the X axis.
- [210] The soft magnetic pattern 600 may be comprised of a first soft magnetic pattern 601, a second soft magnetic pattern 602, a third soft magnetic pattern 603, and a fourth soft magnetic pattern 604. The first soft magnetic pattern 601 is interposed between the

data storage pattern 100 and the first drive pattern 701. The second soft magnetic pattern 602 is interposed between the data storage pattern 100 and the second drive pattern 702. The third soft magnetic pattern 603 is interposed between the data storage pattern 100 and the third drive pattern 703. The fourth soft magnetic pattern 604 is interposed between the data storage pattern 100 and the fourth drive pattern 704.

[211] If the soft magnetic pattern 600 is identical to the magnetic domain wall 120 in magnetization direction, there is repulsion therebetween. If the soft magnetic pattern 600 is contrary to the magnetic domain wall 120 in magnetization direction, there is attraction therebetween. Therefore, through controlling a magnetization direction of the soft magnetic pattern 600, it is able to shift the magnetic domain wall 120 by means of attraction or repulsion. A magnetization direction of the soft magnetic pattern 600 can be set by the drive pattern 700.

[212] Without applying the driving magnetic flux density directly to the data storage pattern 100 from the drive pattern 700, it is able to change a magnetization direction of the soft magnetic pattern 600. A magnetization direction of the soft magnetic pattern 600 causes the magnetic domain wall 120 of the data storage pattern 100 shift to left or right. As a result, the driving magnetic flux density from the driving pattern 700 affects the shift (or movement) of the magnetic domain wall 120 by way of the soft magnetic pattern 600.

[213] For instance, if a magnetization direction set to make the first soft magnetic pattern 601 repulse the magnetic domain wall 120 and make the second soft magnetic pattern 602 attract the magnetic domain wall 120 at the time  $t_1$ , the magnetic domain wall 120 shifts near to the second soft magnetic pattern 602. If a magnetization direction set to make the second soft magnetic pattern 602 repulse the magnetic domain wall 120 and make the first soft magnetic pattern 601 attract the magnetic domain wall 120 at the time  $t_2$ , the magnetic domain wall 120 shifts near to the first soft magnetic pattern 601, moving by a unit area.

[214] For applying the periodical and uneven magnetic flux density to the data storage pattern 100, the drive patterns 700 and the soft magnetic patterns 600 may be formed in the optimum condition by computer simulation, theoretical evaluation, or experimental results.

[215] On the first drive pattern 701 may be disposed a first drive contact plug 751. For electrical connection to the first drive pattern 701, an upper connection 761 may be provided to connect the first drive contact plug 751 therewith.

[216] On the second drive pattern 702 may be disposed a second drive contact plug 752. For electrical connection to the second drive pattern 702, the upper connection 761 may be provided to connect the second drive contact plug 752 therewith. Under the third drive pattern 703 may be disposed a third drive contact plug (not shown). For

electrical connection to the third drive pattern 703, a lower connection (not shown) may be provided to connect the third drive contact plug therewith.

[217] Under the third drive pattern 704 may be disposed a fourth drive contact plug (not shown). For electrical connection to the fourth drive pattern 704, a lower connection (not shown) may be provided to connect the second drive contact plug therewith.

[218] The first driving magnetic flux density  $By_1(x)$  is generated by applying a forward current to the first drive pattern 701. The second driving magnetic flux density  $By_2(x)$  is generated by applying a forward current to the second drive pattern 702. The third driving magnetic flux density  $By_3(x)$  is generated by applying a forward current to the third drive pattern 703. The fourth driving magnetic flux density  $By_4(x)$  is generated by applying a forward current to the fourth drive pattern 704.

[219] According to another modification by the present invention, the drive pattern 700 is not restrictive to the feature with fixed width and thickness. Namely, the drive pattern is variable in number and shape. Further, the upper connections 761 and the lower connections are also out of restriction as illustrated above. As also, the drive contact plugs 751 and 752 may be changed in various forms in need of those skilled in the art.

[220] FIG. 27 is a flow chart showing a procedure of shifting the magnetic domain walls in accordance with an embodiment of the present invention.

[221] In order to shift the magnetic domain walls of the data storage pattern 100, first, it aligns the magnetic domain walls 120 of the data storage pattern 100 to a direction (S100). The magnetic domain wall aligning step S100 may be carried out along with the writing operation, as aforementioned relevant to FIGs. 8 and 10. Namely, it is able to align the magnetic domain wall 120 adjacent to the unit magnetic domain 110 at the same time while storing data into the unit magnetic domain 110. Meantime, if the magnetic domain walls 120 have been already aligned to a direction, the aligning step S100 will be skipped.

[222] Thereafter, it sets the number of cells to be moved (S200). Here, the cell means the unit area as aforementioned. For the reading (or reproducing) or writing (recording or programming) operation, the number of cells to be shifted is counted in order to move the cells storing data in the step S200.

[223] Next, it determines a shifting direction (S300). The magnetic domain walls of the MFD-driven MGWM memory device can be designed to shift unilaterally or bilaterally. If the magnetic domain walls are designed to shift bilaterally, the step S300 for determining the shifting direction may be conducted.

[224] Then, it applies the driving magnetic flux density, which is spatially unevenly periodically generated, to the data storage pattern 100 (S400). This uneven magnetic flux density forces the magnetic domain wall 120 to shift toward the selected direction.

[225] The uneven driving magnetic flux density is variable along time and may be in a

pulse type. For instance, the driving magnetic flux density is generated by a current flowing through the drive pattern. Namely, the current flowing through the drive pattern may be fluctuated and oscillated in pulses.

- [226] To shift the magnetic domain walls, the driving magnetic flux density may be prepared in plurality, i.e.,  $By_1(x) \sim By_n(x)$ . The driving magnetic flux densities may be applied to the data storage pattern 100 in time intervals. Responding to the driving magnetic flux densities, the magnetic domain walls are able to shift in predetermined ranges.
- [227] Afterward, it checks up the set number of cells (S500). If the magnetic domain walls have shifted as many as the set number of cells, the driving magnetic flux density will not be further applied to the data storage pattern 100.
- [228] In a case of storing data into a designated unit magnetic domain, it further includes a writing step. Meanwhile, in reading data from the designated unit magnetic domain, it further includes a reproducing step.
- [229] After completing the recording or reproducing step, the procedure may be further comprised of a step for returning to the initial state.
- [230] FIGs. 28 is view illustrating features of shifting the magnetic domain walls, showing the data storage pattern (28(A)), the drive magnetic flux density for shifting the magnetic domain walls to right (28(B)), and the drive magnetic flux density for moving the magnetic domain walls to left (29(C)), respectively.
- [231] Referring to FIG. 28(A), the data storage pattern 100 extends along the X axis. The magnetic domains 110 of the data storage pattern may be parallel or anti-parallel to the X axis. The magnetic domain walls 120 of the data storage pattern 100 may be aligned to the Y axis. The data storage pattern 100 may be comprised of the pinning region 130a as shown in FIGs. 11 and 13. The pinning region 130a is provided to block a shift of the magnetic domain wall 120. The pinning regions 130a may be periodically arranged on the data storage pattern 100. In a static condition, the magnetic domain wall 120 is placed in the pinning region 130a.
- [232] Referring to FIG. 28(B), there is shown the driving magnetic flux density formable by the structure or modification of the drive pattern 700 illustrated in FIG. 25 in order to shift the magnetic domain wall 120 to left. The first driving magnetic flux density  $By_1(x)$  is applied to the data storage pattern 100 at the time t1. The first driving magnetic flux density  $By_1(x)$  forces the magnetic domain wall 120 to shift to the direction (i.e., left) along the increase of the first driving magnetic flux density  $By_1(x)$  in correspondence with the maximum point of the first driving magnetic flux density  $By_1(x)$ .
- [233] Continuously, at the time t2, the second driving magnetic flux density  $By_2(x)$  may be applied to the data storage pattern 100. Then, the magnetic domain wall 120, which has

shifted to the maximum point of the first driving magnetic flux density  $By_1(x)$ , further moves to the left in correspondence with the maximum point of the second driving magnetic flux density  $By_2(x)$ . During this, the second driving magnetic flux density  $By_2(x)$  is variable along time so as to prevent the magnetic domain wall 120 from shifting over the pinning region 130a. In other words, an amount of current flowing through the second drive pattern 720 generating the second driving magnetic flux density  $By_2(x)$  is reduced to make the magnetic domain wall 120 stop shifting at the pinning region 130a. The current supplied into the drive pattern 700 may be formed in a pulse.

[234] Referring to FIG. 28(C), there is shown the driving magnetic flux density formable by the structure or modification of the drive pattern 700 illustrated in FIG. 25 in order to shift the magnetic domain wall 120 to right. The third driving magnetic flux density  $By_3(x)$  is applied to the data storage pattern 100 at the time t3. The third driving magnetic flux density  $By_3(x)$  forces the magnetic domain wall 120 to shift to the direction (i.e., right) along the increase of the third driving magnetic flux density  $By_3(x)$  in correspondence with the maximum point of the third driving magnetic flux density  $By_3(x)$ .

[235] Continuously, at the time t4, the fourth driving magnetic flux density  $By_4(x)$  may be applied to the data storage pattern 100. Then, the magnetic domain wall 120, which has shifted to the maximum point of the third driving magnetic flux density  $By_3(x)$ , further moves to the right in correspondence with the maximum point of the fourth driving magnetic flux density  $By_4(x)$ . During this, the fourth driving magnetic flux density  $By_4(x)$  is variable along time so as to prevent the magnetic domain wall 120 from shifting over the pinning region 130a. In other words, an amount of current flowing through the drive pattern generating the fourth driving magnetic flux density  $By_4(x)$  is reduced to make the magnetic domain wall 120 stop shifting at the pinning region 130a.

[236] Returning to FIG. 25, the first and fourth driving magnetic flux densities,  $By_1(x)$  and  $By_4(x)$ , may be formed by a direction of current flowing through the first driving pattern 710. Meanwhile, the second and third driving magnetic flux densities,  $By_2(x)$  and  $By_3(x)$ , may be formed by a direction of current flowing through the second driving pattern 720.

[237] FIGs. 29 is view illustrating a feature of shifting the magnetic domain walls of the data storage pattern in accordance with an embodiment of the present invention.

[238] In the data storage pattern 100, at least two of the unit magnetic domains, 110c and 110d, may be successively assigned to the same magnetization direction. In this case, there may not be present any magnetic domain wall between the unit magnetic domains 110c and 110d that have been sequentially aligned to the same magnetization direction. Therefore, when the driving magnetic flux density is applied to the data storage pattern 100, the magnetic domains 110c and 110b of the data storage pattern

100 are able to shift to left or right. Consequently, even though the data storage pattern 100 includes the unit magnetic domains 110c and 110d sequentially magnetized to the same direction, the feature of shifting the magnetic domain wall 120 is same as that illustrated by FIGs. 28. But, the data storage pattern 100 includes at least one magnetic domain wall.

[239] According to an embodiment of the present invention, it will be understood about available combinations and modifications by those skilled in the art even without details for them.

[240] The method of forming the memory device in accordance with an embodiment of the present invention is comprised of forming a data storage pattern including pluralities of magnetic domain walls and at least one magnetic domain on a substrate, and forming at least one drive pattern, for generating a driving magnetic flux density, around the data storage pattern. The driving magnetic flux density enables the magnetic domain wall of the data storage pattern to shift.

[241] Returning to FIG. 8, the substrate 10 may be made of a semiconductor or glass. It is also permissible to provide a drive circuit, for activating the memory device, on the substrate.

[242] The steps of forming the data storage pattern 100 and the drive pattern 700 are accomplished by the technology of photolithography and patterning. The data storage pattern may be formed in a plural layer structure. Thus, the steps of forming the data storage pattern 100 and the drive pattern 700 may be further comprised of a planarizing process.

[243] The method of forming the memory device in accordance with an embodiment of the present invention may further include at least one of the steps of forming the writing structure, forming the reproducing structure, forming the pinning structure, forming the MDW-aligning structure, forming the soft magnetic pattern, and forming the shielding structure.

### **Industrial Applicability**

[244] The present invention disclosed herein is applicable to memory devices capable of storing data by means of magnetic force.

## Claims

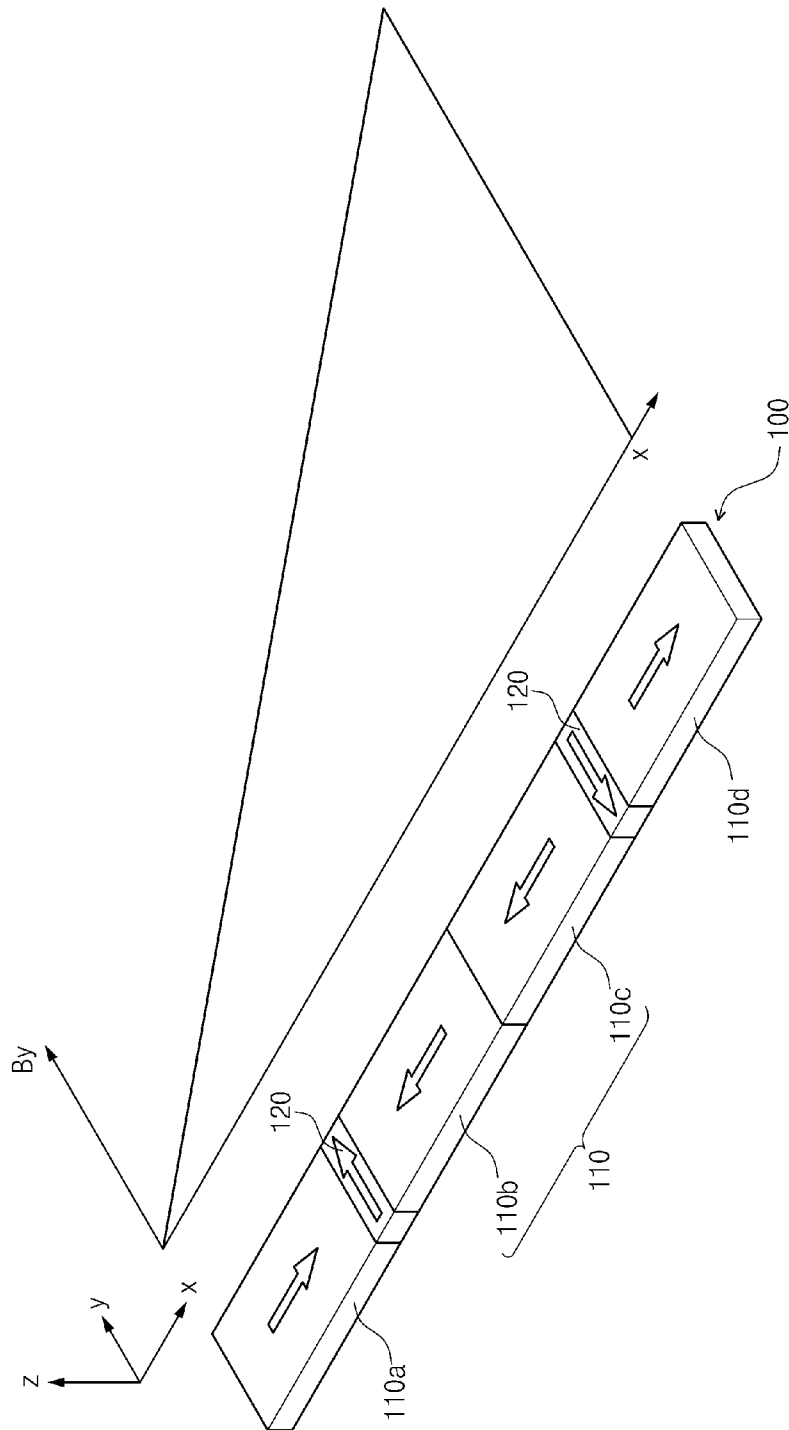
- [1] A memory device comprising:  
a data storage pattern including pluralities of magnetic domains and magnetic domain walls; and  
at least a drive pattern generating a driving magnetic flux density for the data storage pattern,  
wherein the magnetic domain walls of the data storage pattern shifts by the driving magnetic flux density.
- [2] The memory device as set forth in claim 1, wherein the driving magnetic flux density varies in intensity by positional variation along a progress direction of the data storage pattern.
- [3] The memory device as set forth in claim 1, wherein the magnetic domain walls of the data storage pattern are conditioned in the same magnetization direction.
- [4] The memory device as set forth in claim 1, further comprising: a magnetic domain wall aligning structure aligning the magnetic domain walls of the data storage pattern to the same magnetization direction.
- [5] The memory device as set forth in claim 1, wherein the driving magnetic flux density operates in spatially periodic distribution along a progress direction of the data storage pattern.
- [6] The memory device as set forth in claim 1, wherein the magnetization direction of the magnetic domain walls are perpendicular to the magnetization directions of the magnetic domains .
- [7] The memory device as set forth in claim 1, wherein the magnetization directions of the magnetic domains are parallel or anti-parallel to a progress direction of the data storage pattern.
- [8] The memory device as set forth in claim 1, further comprising: a writing structure disposed around the data storage pattern and changing the magnetization directions of the magnetic domains.
- [9] The memory device as set forth in claim 8, wherein the writing structure magnetizes the magnetic domains to be parallel or anti-parallel with a progress direction of the data storage pattern.
- [10] The memory device as set forth in claim 1, further comprising: a reproducing structure disposed around the data storage pattern and reading the magnetization directions of the magnetic domains.
- [11] The memory device as set forth in claim 1, wherein the data storage pattern comprises pluralities of unit areas arranged along a progress direction of the data storage pattern;

wherein each unit area includes a unit magnetic domain, or a unit magnetic domain and a magnetic domain wall adjacent to the unit magnetic domain; and wherein the driving magnetic flux density operates in distribution with a spatial period that corresponds to a length of the unit area or integer times of the length along a progress direction of the data storage pattern.

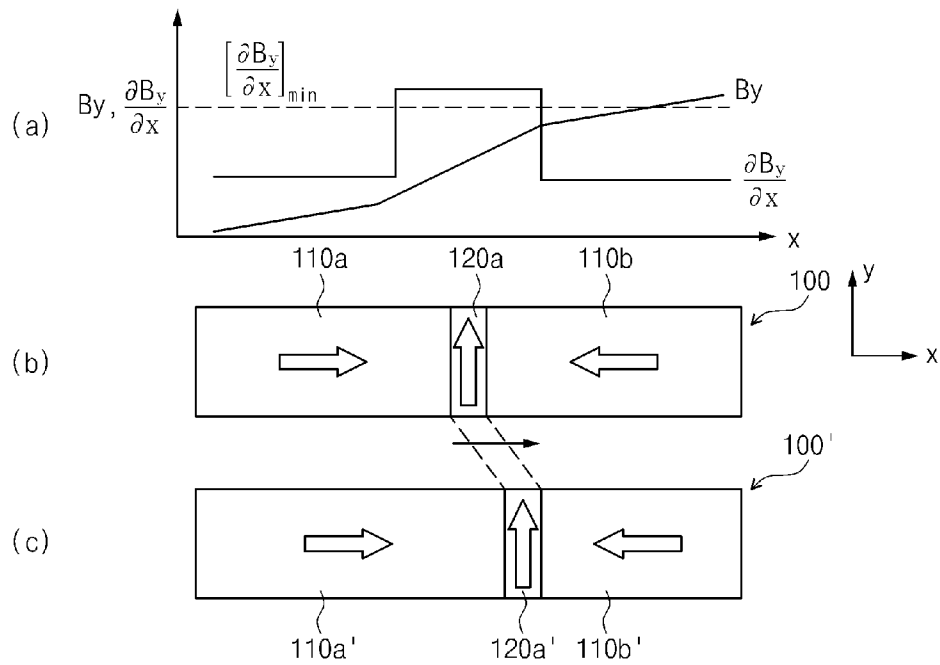
- [12] The memory device as set forth in claim 11, wherein the drive pattern is included in plurality with respect to the unit areas;  
wherein the drive patterns respective to the unit areas are same with each other in structure.
- [13] The memory device as set forth in claim 11, wherein the driving magnetic flux density at least has the maximum point or a point changing a sign of a gradient of the driving magnetic flux density.
- [14] The memory device as set forth in claim 1, wherein the driving magnetic flux density is less than the maximum intensity for changing a magnetization direction of the magnetic domain and higher than the minimum intensity for shifting the magnetic domain wall.
- [15] The memory device as set forth in claim 1, wherein the data storage pattern comprises at least one of ferromagnetic, ferromagnetic alloy, and ferrimagnetic materials.
- [16] The memory device as set forth in claim 15, wherein the data storage pattern comprises at least one of nonmagnetic and anti-ferromagnetic materials.
- [17] The memory device as set forth in claim 1, wherein the data storage pattern is shaped in one of a strip line, an open loop, and a serpentine form.
- [18] The memory device as set forth in claim 1, wherein the drive pattern intersects a progress direction of the data storage pattern in a predetermined angle.
- [19] The memory device as set forth in claim 1, wherein the drive pattern has an uneven width for irregular spatial distribution.
- [20] The memory device as set forth in claim 1, wherein the drive pattern extends along a progress direction of the data storage pattern so as to periodically apply the driving magnetic flux density along the progress direction of the data storage pattern,  
wherein the drive pattern varies in one of width and thickness so as to periodically apply the driving magnetic flux density.
- [21] The memory device as set forth in claim 1, wherein the data storage pattern further comprises a pinning region for pinning the magnetic domain wall.
- [22] The memory device as set forth in claim 21, wherein the pinning region is different from an adjacent region of the pinning region in at least one of width, thickness, material, curvature, and physical property.

- [23] The memory device as set forth in claim 21, further comprising: a pinning structure disposed around the drive pattern, wherein the pinning structure includes at least one of a multi-level film, a spring magnet, an anti-ferromagnetic material, and a soft magnetic material.
- [24] The memory device as set forth in claim 1, further comprising: a shielding structure disposed around the drive pattern and shielding the driving magnetic flux density generated by the drive pattern.
- [25] The memory device as set forth in claim 1, further comprising: a soft magnetic pattern changing spatial distribution of the driving magnetic flux density generated by the drive pattern, wherein the soft magnetic pattern is configured to make the driving magnetic flux density change in intensity by positional variation along a progress direction of the data storage pattern.
- [26] An operating method of the memory device as described in claim 1, wherein a current flowing through the drive pattern varies by time.
- [27] An operating method of the memory device as described in claim 1, wherein a current flowing through the drive pattern is applied in a pulse.
- [28] A forming method of a memory device, comprising:  
forming a data storage pattern including pluralities of magnetic domains and magnetic domain walls on a substrate; and  
forming at least one drive pattern, for generating a driving magnetic flux density, around the data storage pattern,  
wherein the driving magnetic flux density enables the magnetic domain wall of the data storage pattern to shift.

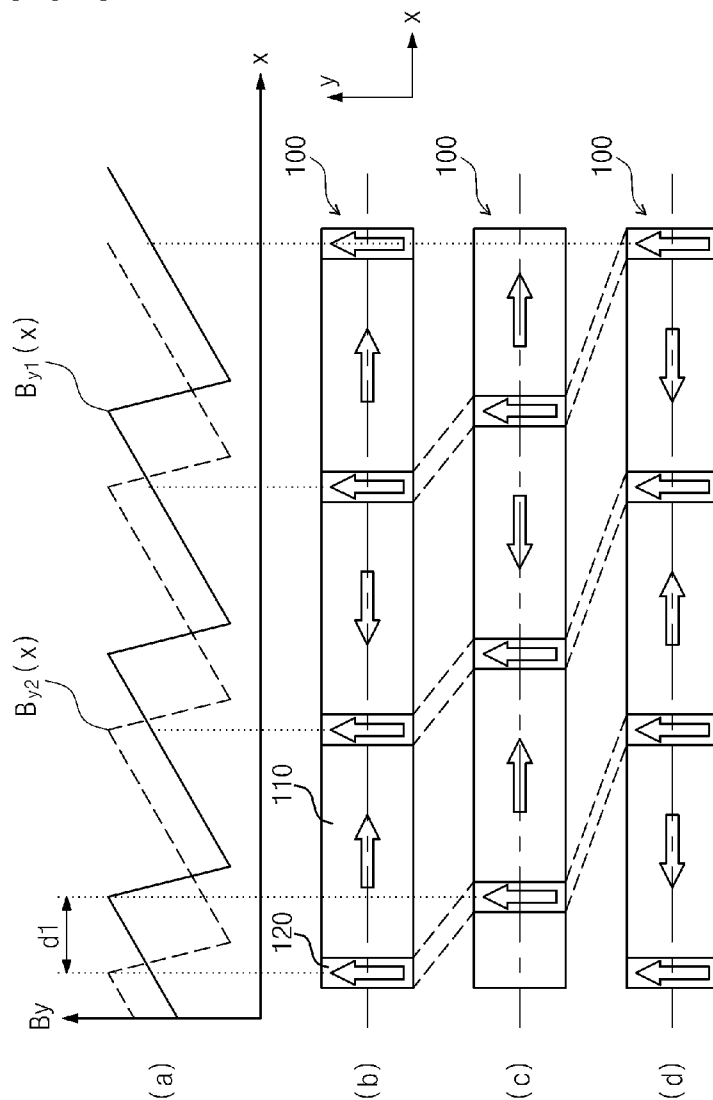
[Fig. 1]



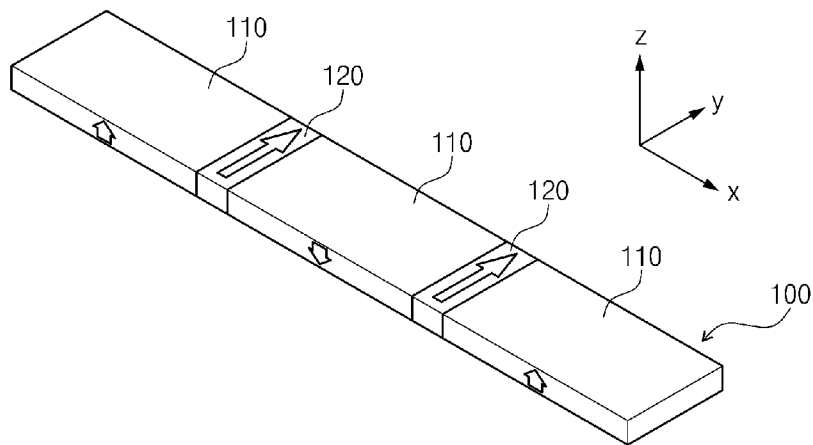
[Fig. 2]



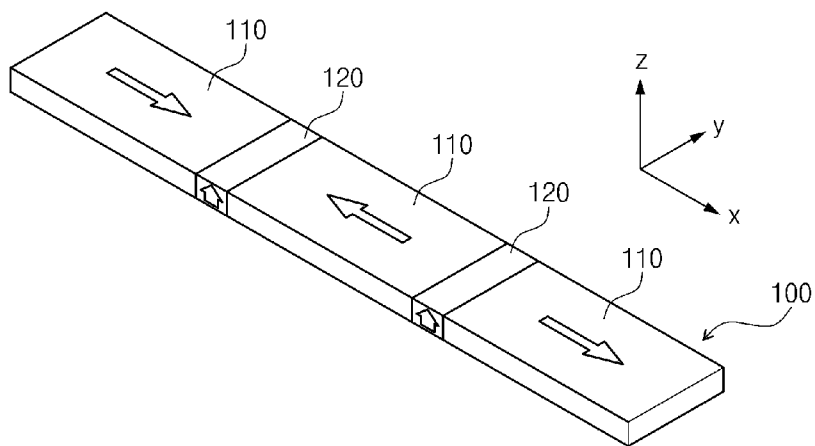
[Fig. 3]



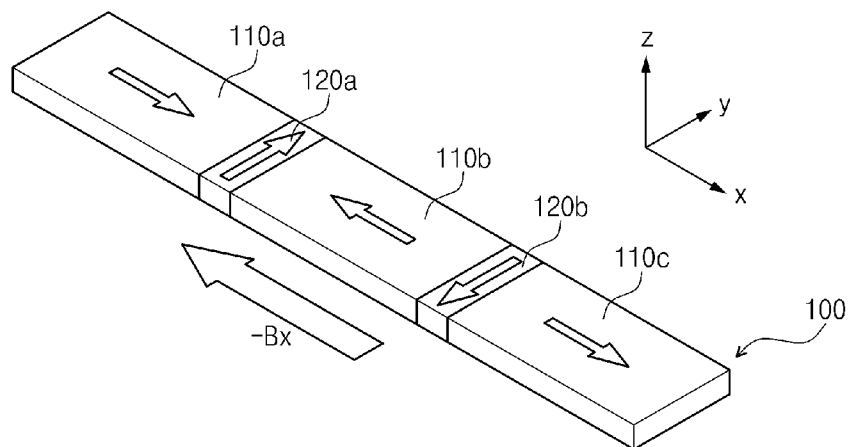
[Fig. 4]



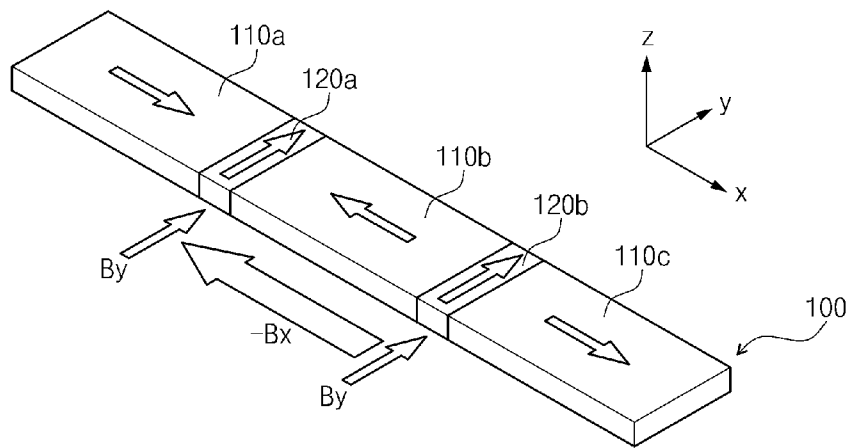
[Fig. 5]



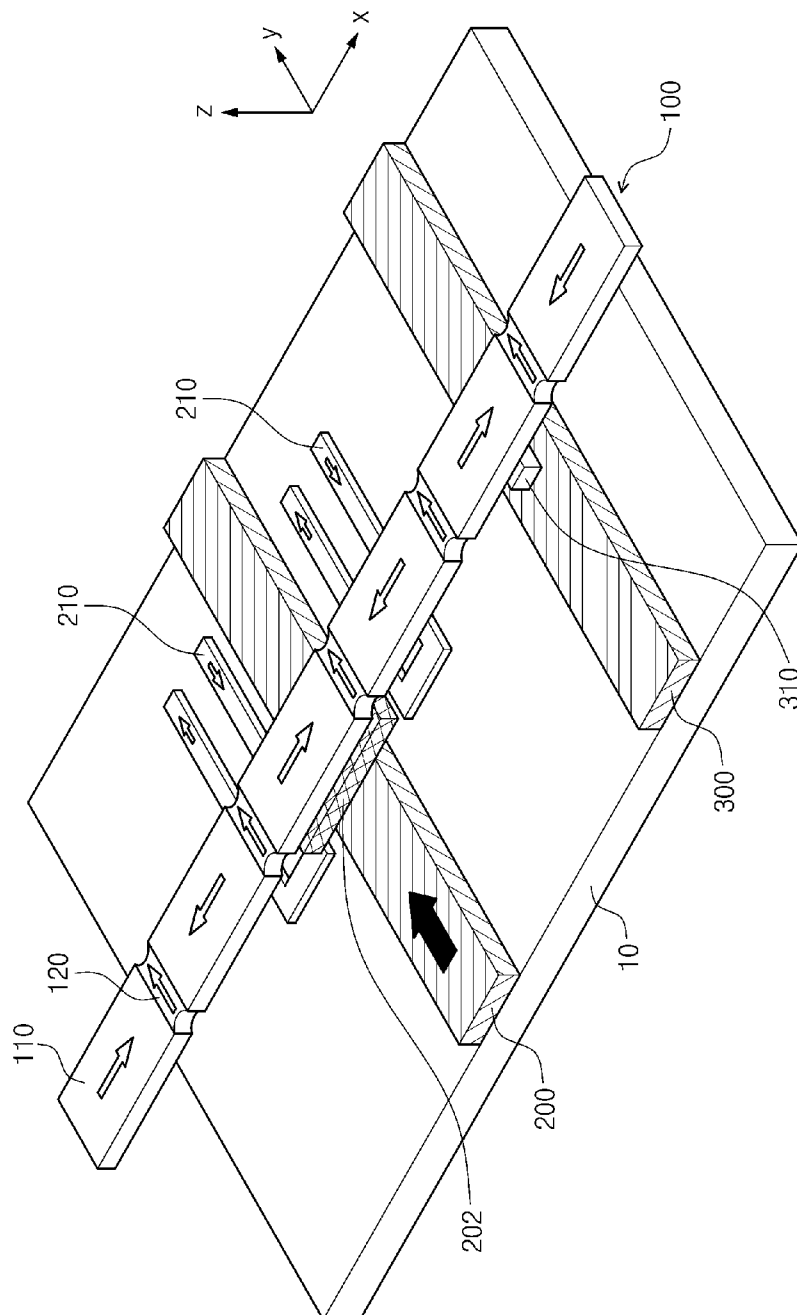
[Fig. 6]



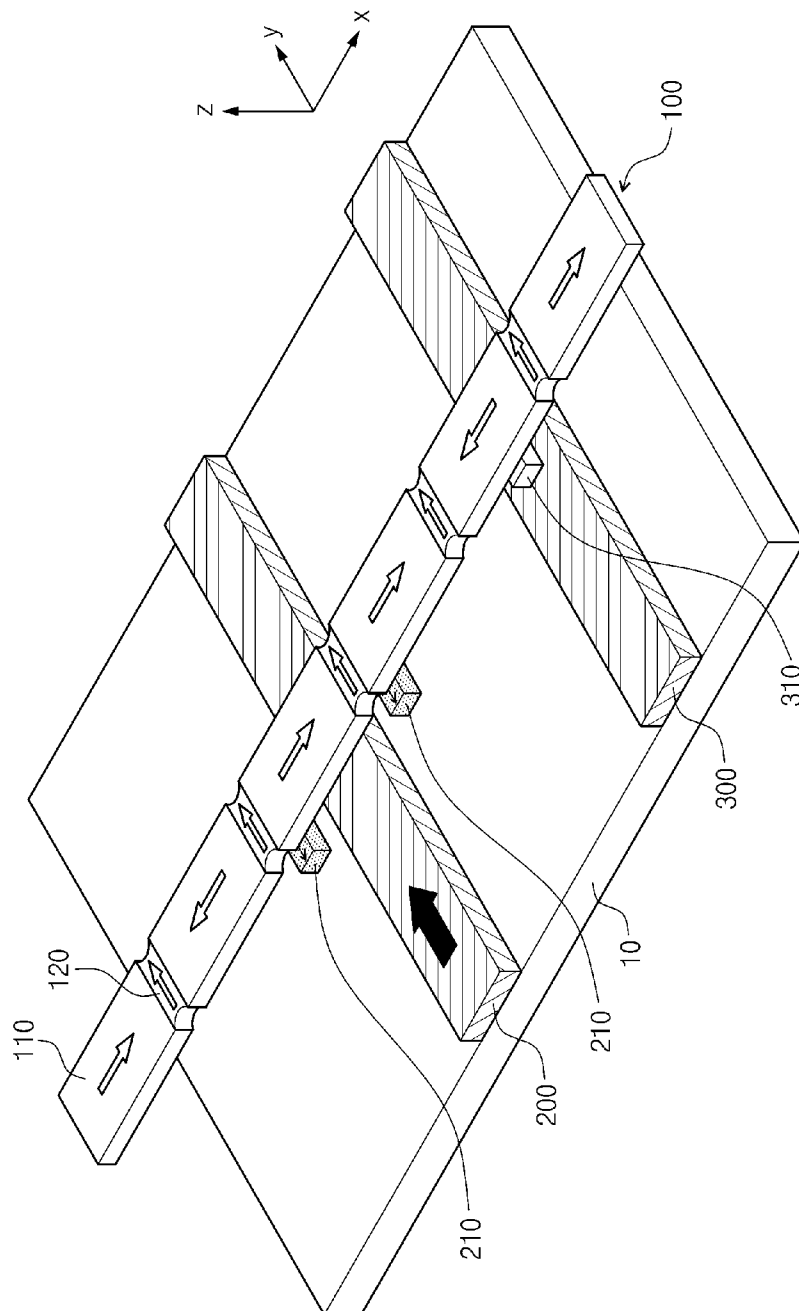
[Fig. 7]



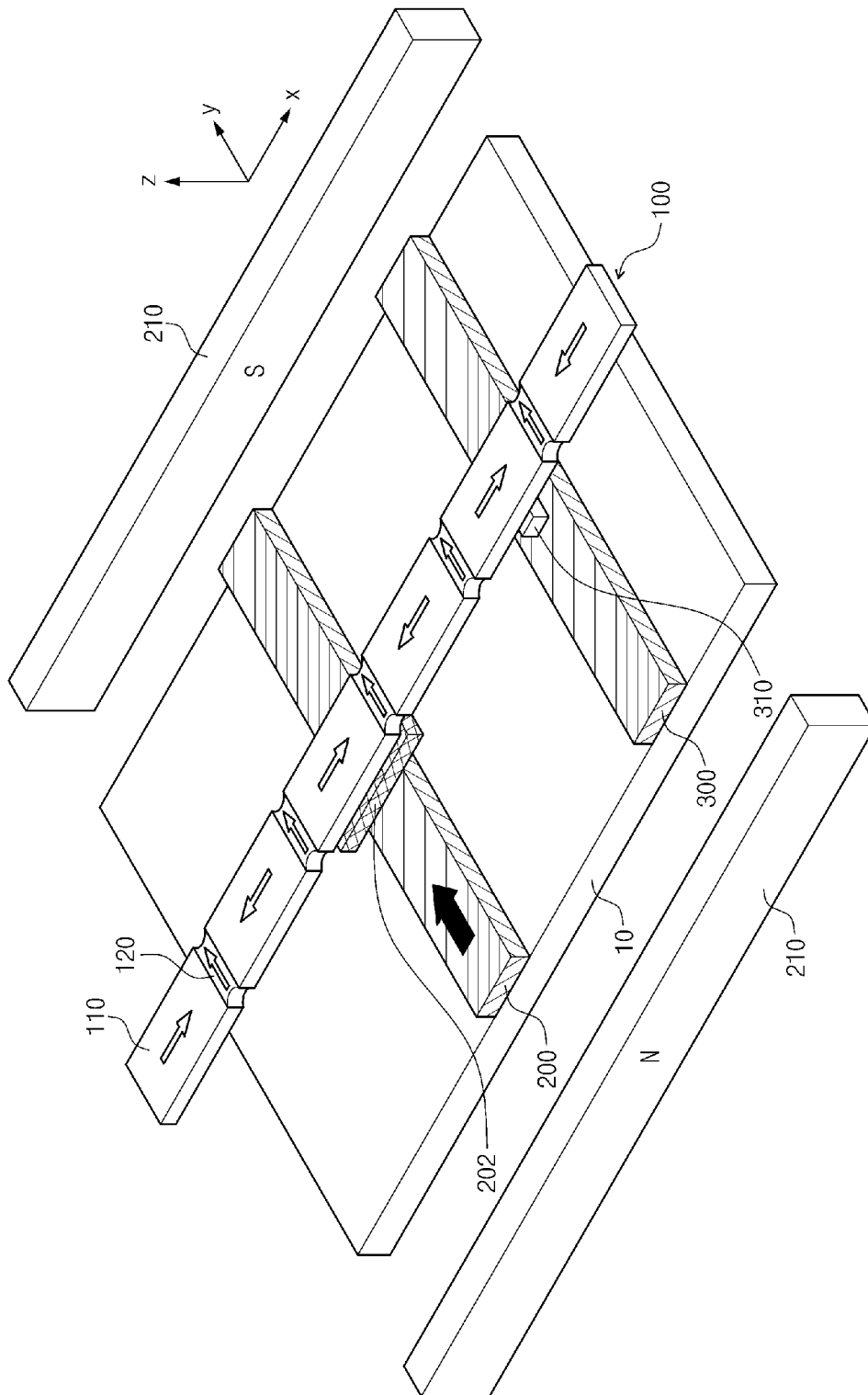
[Fig. 8]



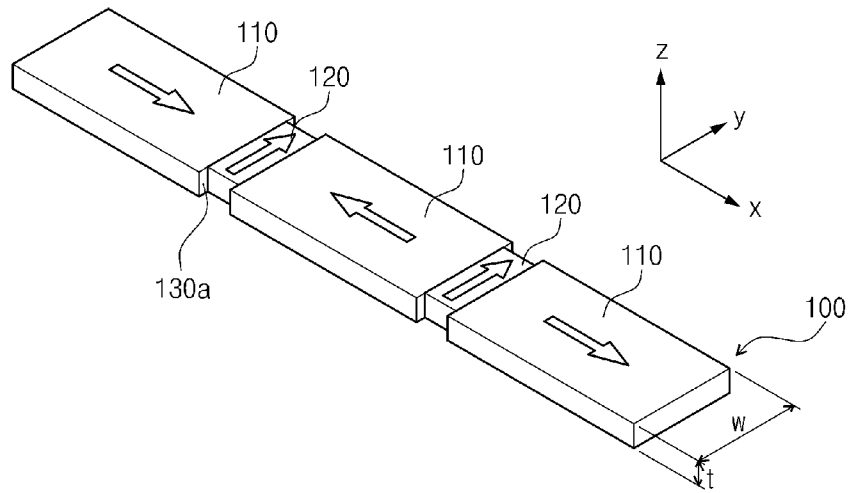
[Fig. 9]



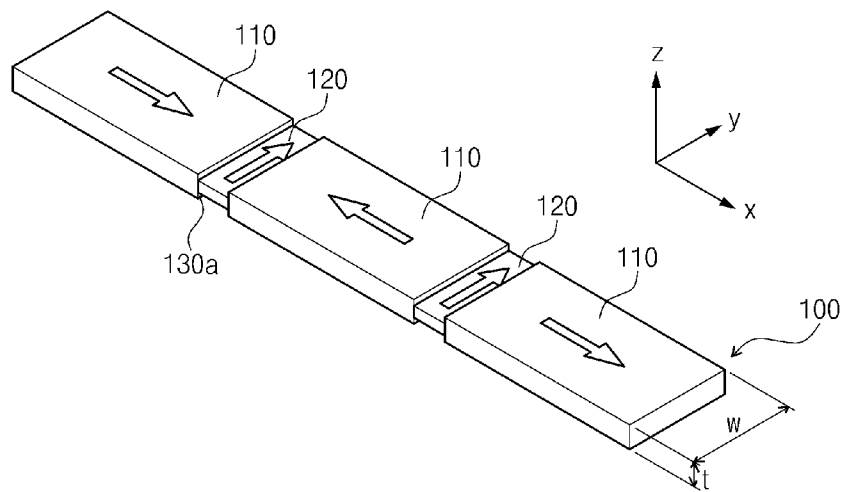
[Fig. 10]



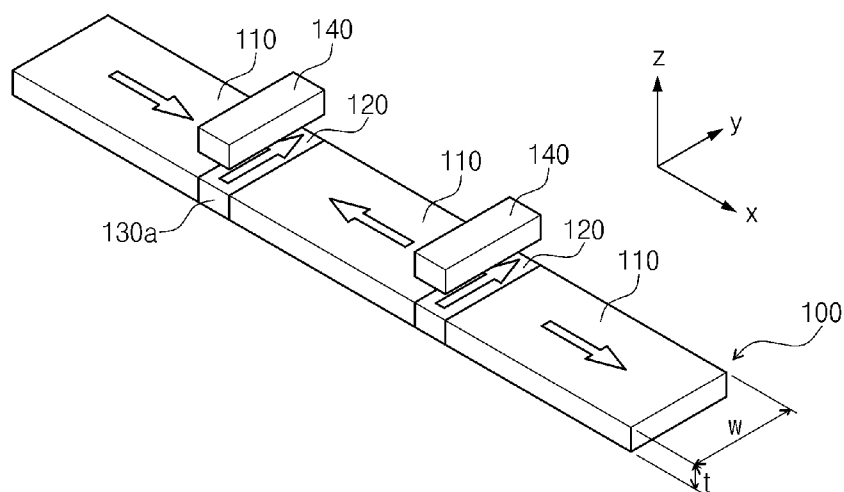
[Fig. 11]



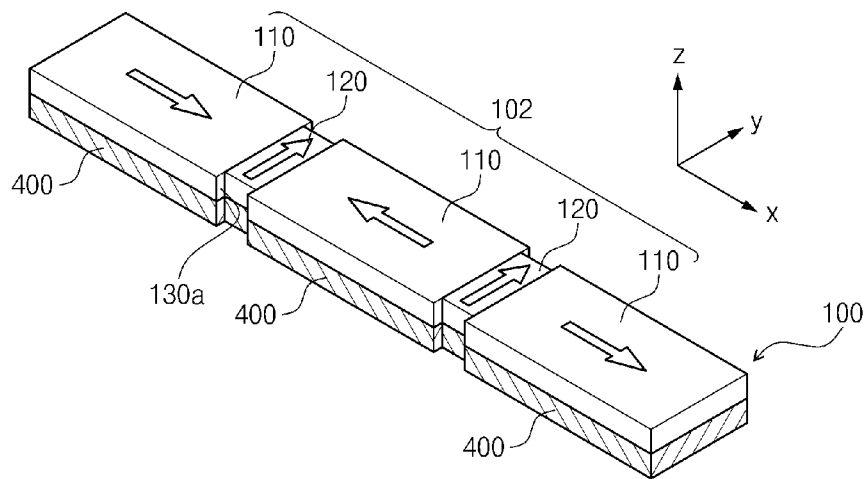
[Fig. 12]



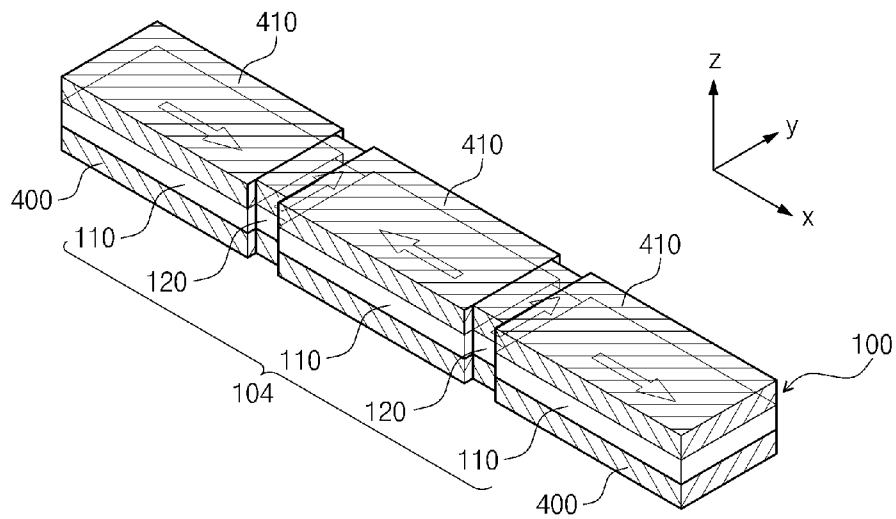
[Fig. 13]



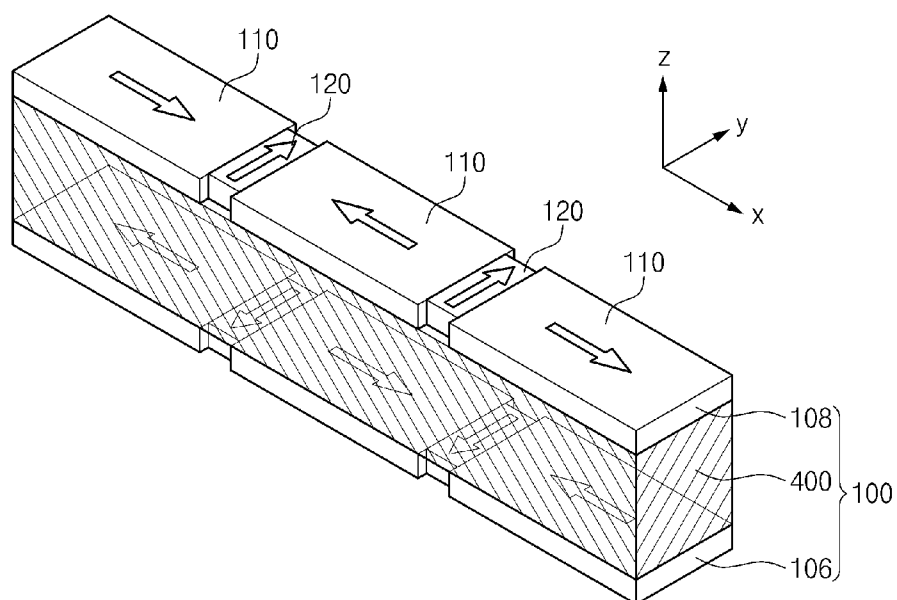
[Fig. 14]



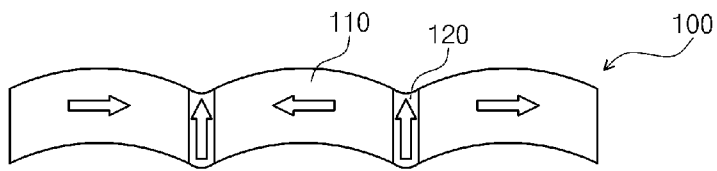
[Fig. 15]



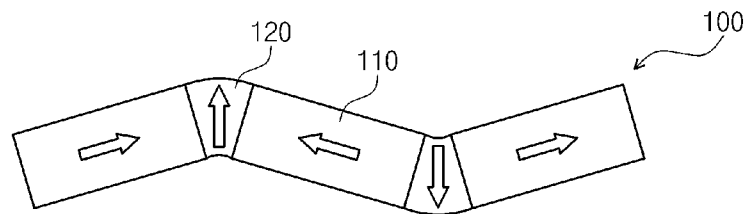
[Fig. 16]



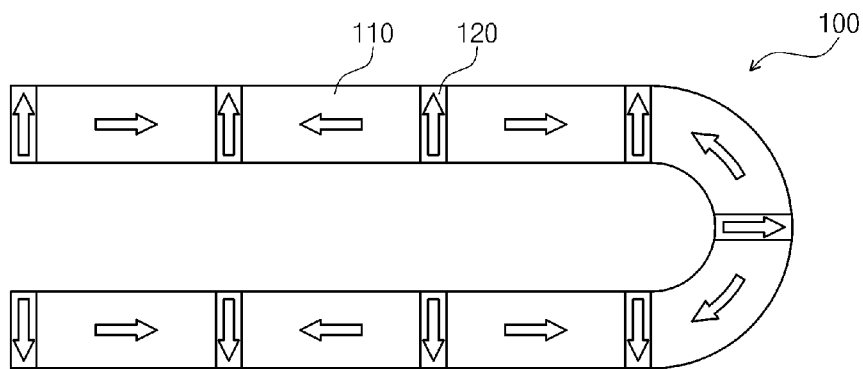
[Fig. 17]



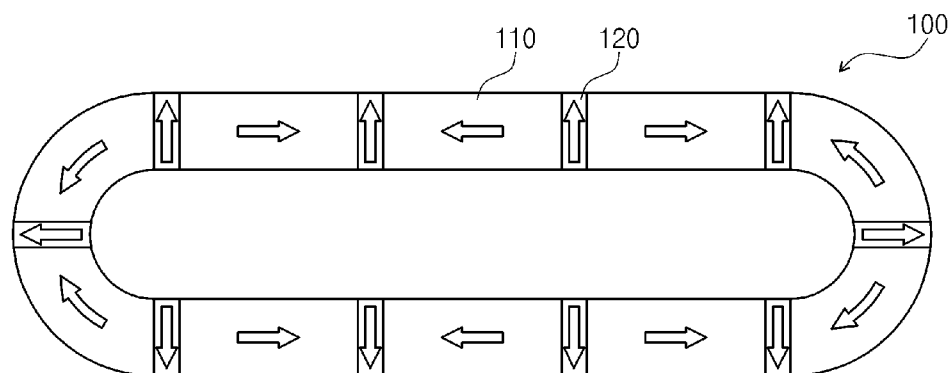
[Fig. 18]



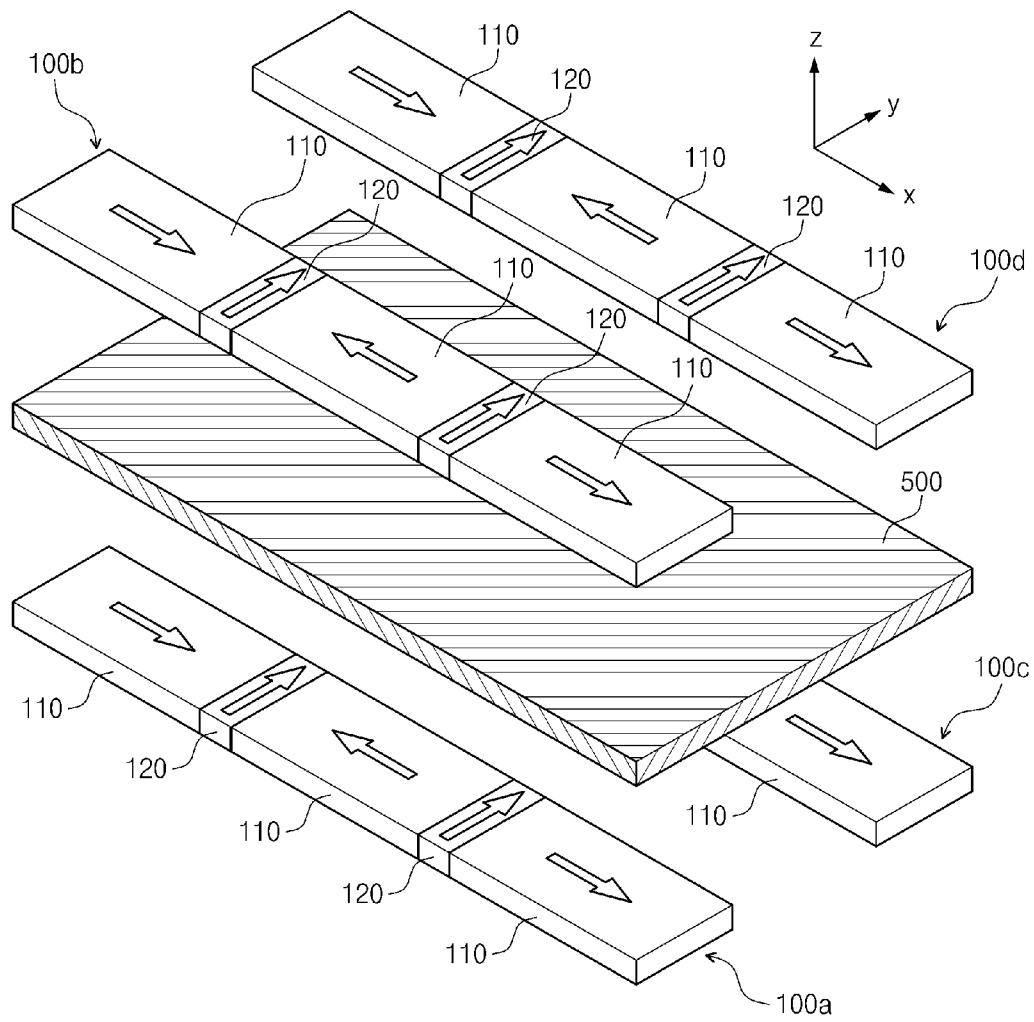
[Fig. 19]



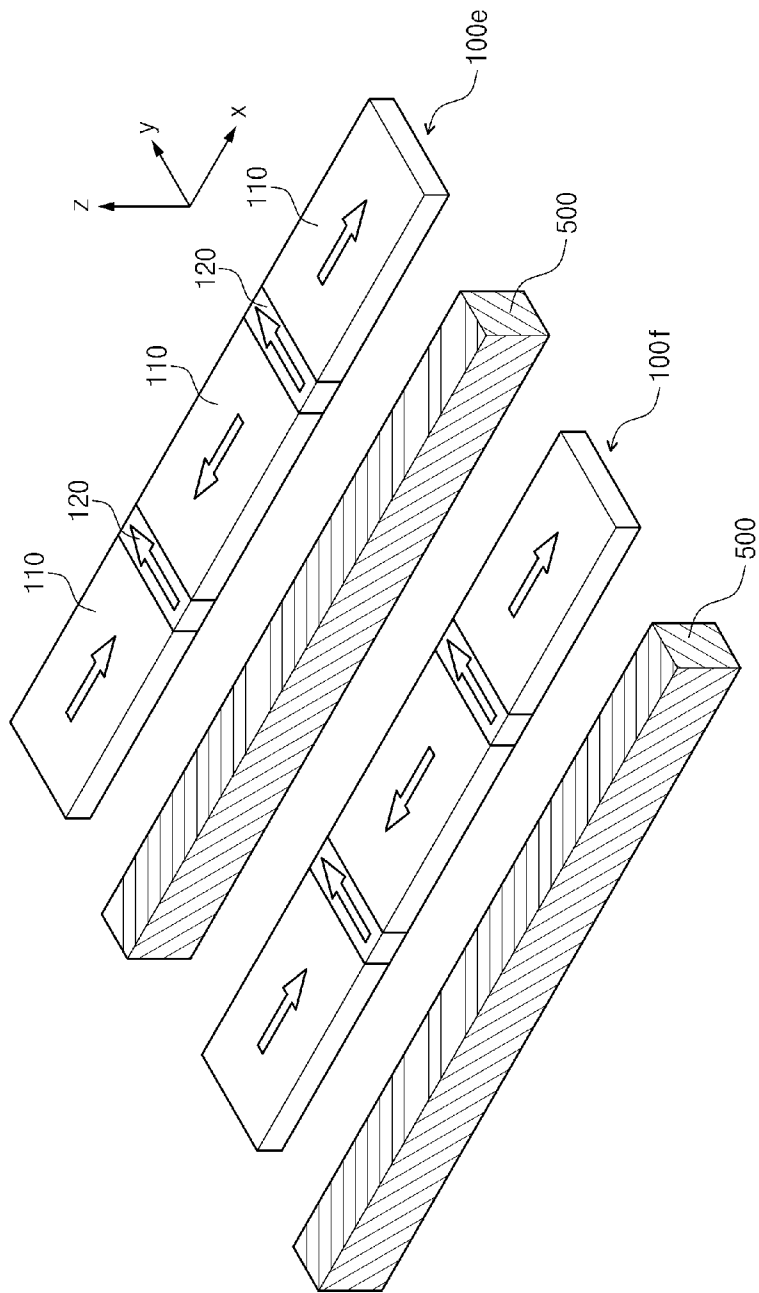
[Fig. 20]



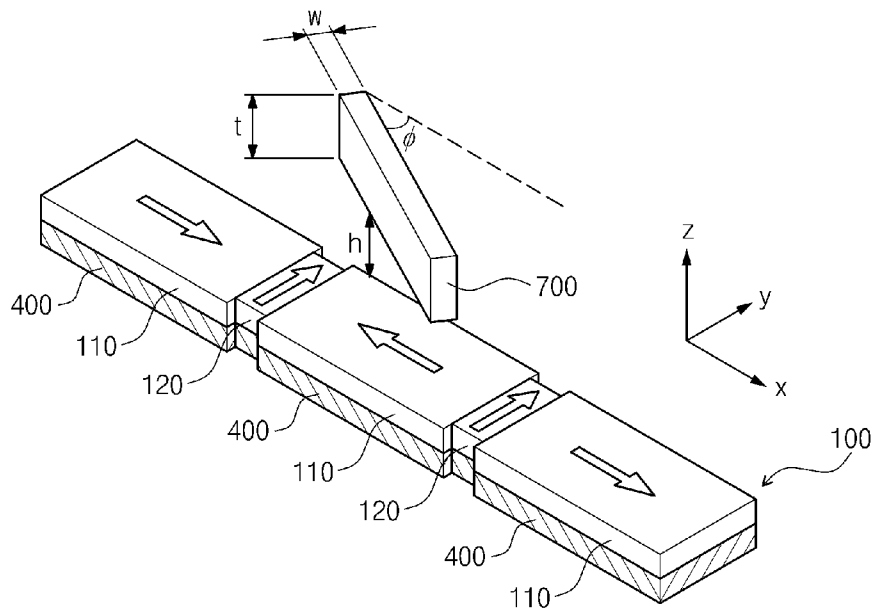
[Fig. 21]



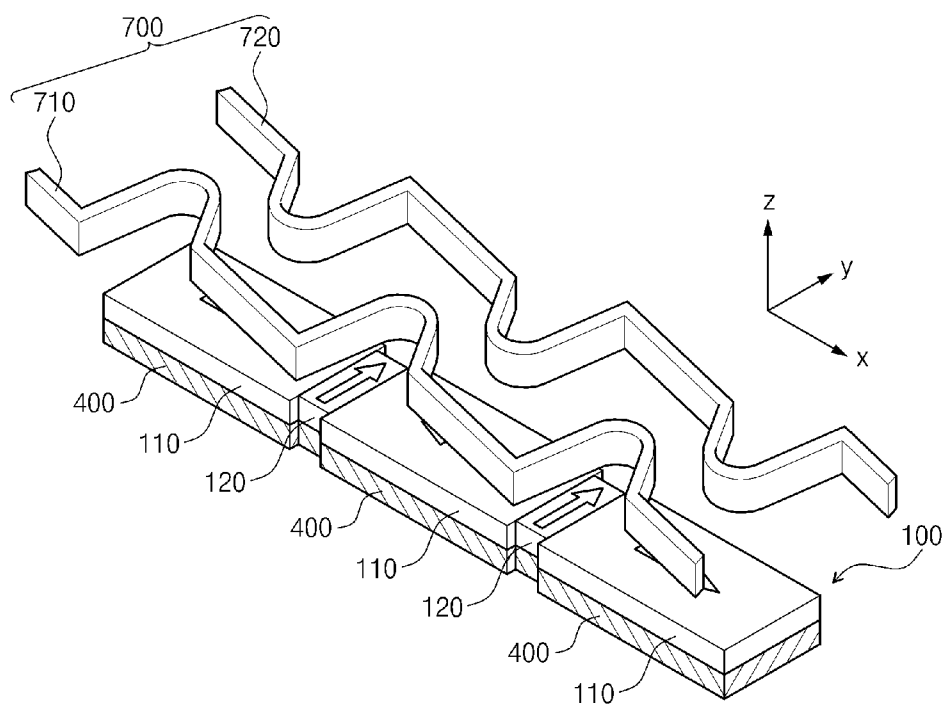
[Fig. 22]



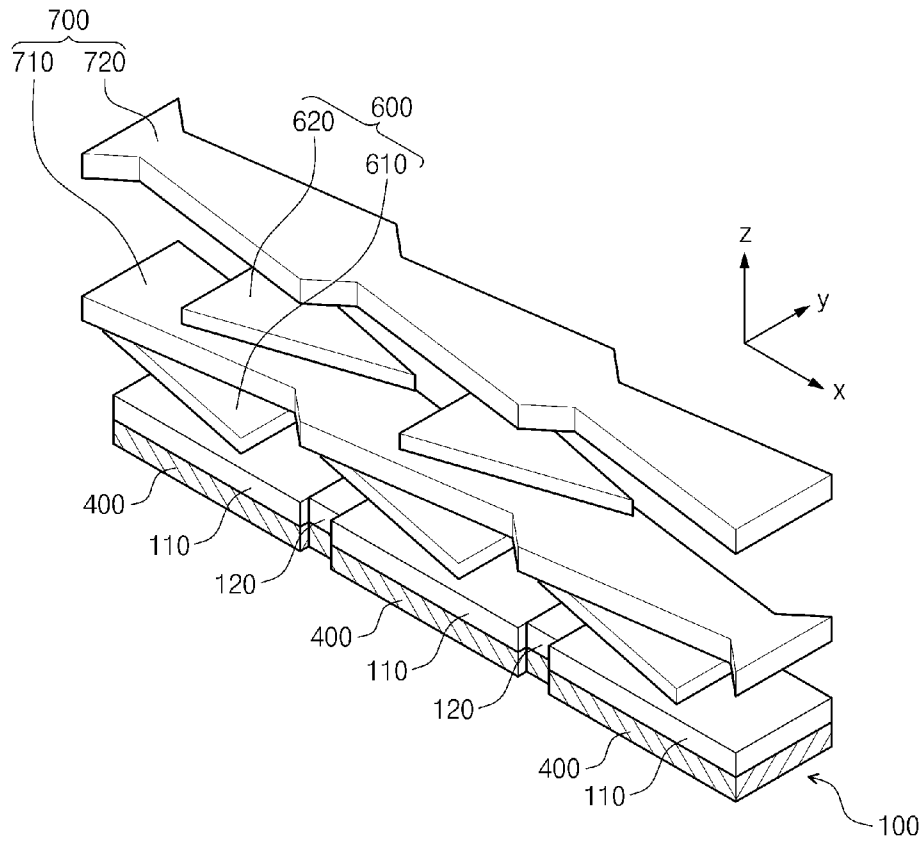
[Fig. 23]



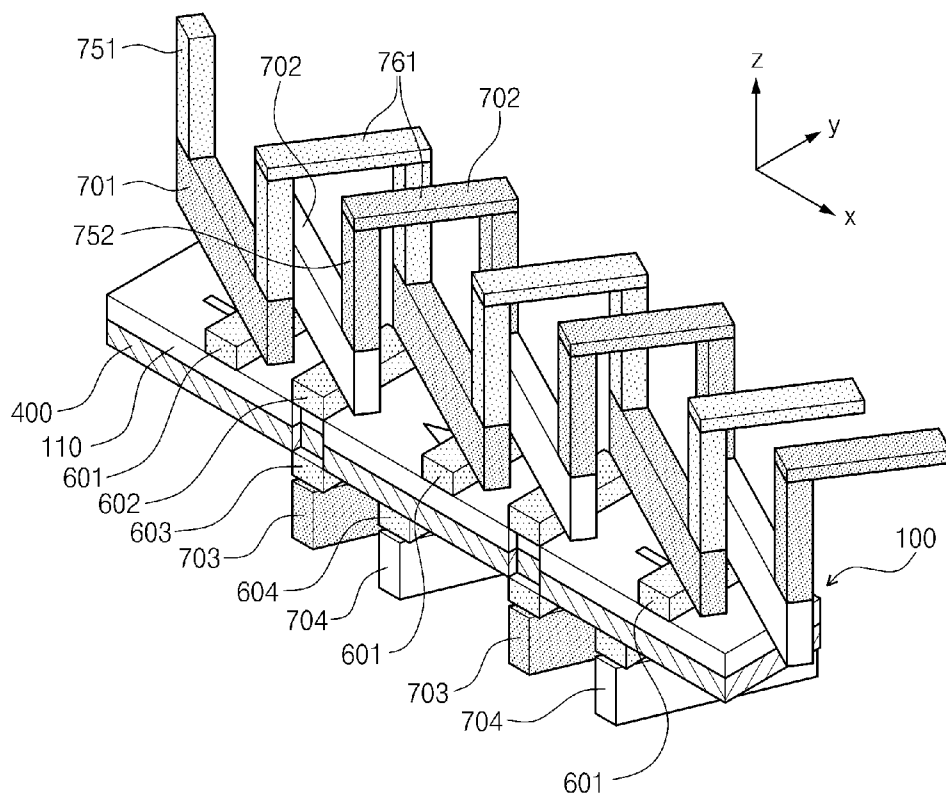
[Fig. 24]



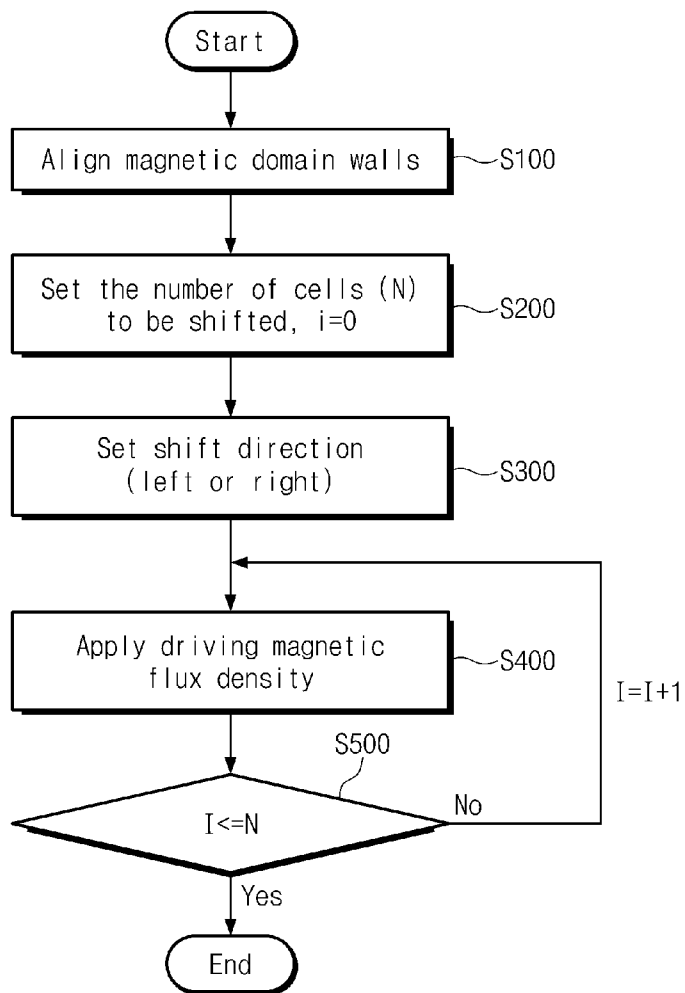
[Fig. 25]



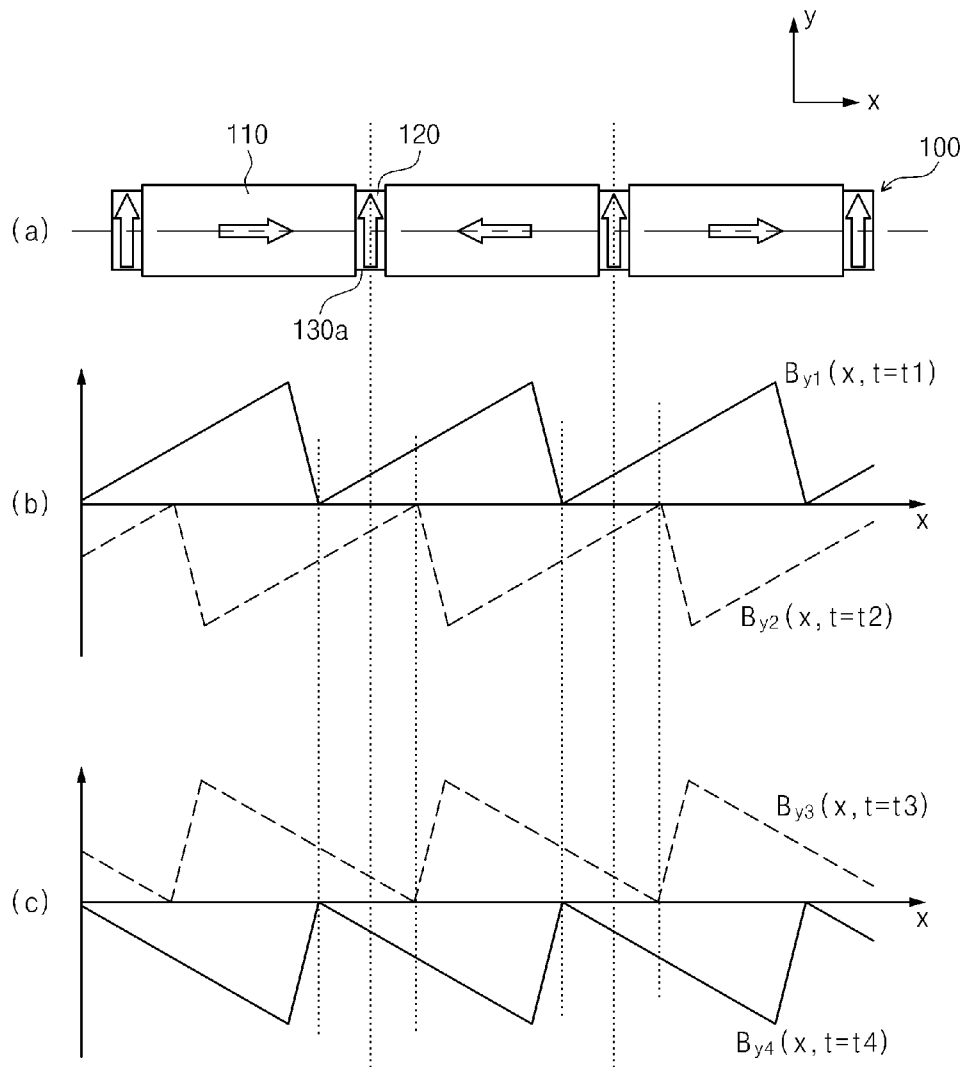
[Fig. 26]



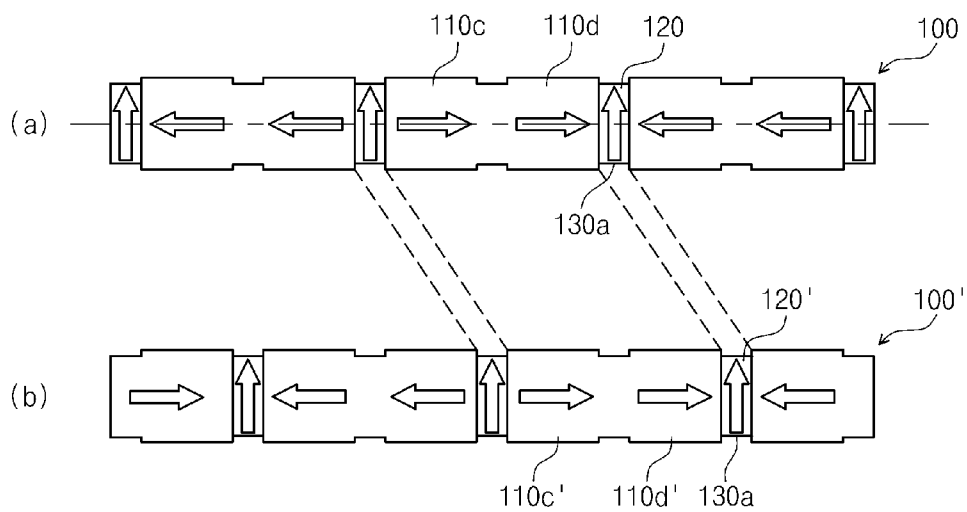
[Fig. 27]



[Fig. 28]



[Fig. 29]



**A. CLASSIFICATION OF SUBJECT MATTER***G11B 5/00(2006.01)i*

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

IPC 8: G11B 5/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean Utility Models and applications for Utility Models since 1975

Japanese Utility Models and application for Utility Models since 1975

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKIPASS(KIPO internal) "dat, storage, magnetic, domain, wall, flux, density, driven, movement, memory, pattern"

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category* | Citation of document, with indication, where appropriate, of the relevant passages                         | Relevant to claim No. |
|-----------|------------------------------------------------------------------------------------------------------------|-----------------------|
| A         | US 2007/0183188 A1 (KEE-WON KIM et al.) 09 August 2007.<br>See paragraphs [0036] - [0078]; figures 1-6.    | 1-28                  |
| A         | US 2003/0117837 A1 (WAN-JUN PARK et al.) 26 June 2003.<br>See paragraphs [0029] - [0039]; figures 1 and 2. | 1-28                  |
| A         | JP 2007-073103 A (SHARP CORP.) 22 March 2007.<br>See paragraphs [0104] - [0191]; figures 1-12.             | 1-28                  |
| A         | US 2006/0108655 A1 (JOEL A. DREWES) 25 May 2006.<br>See Paragraphs [0019] - [0033]; figures 1-4.           | 1-28                  |



Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

02 MAY 2008 (02.05.2008)

Date of mailing of the international search report

**02 MAY 2008 (02.05.2008)**

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Korean Intellectual Property Office  
Government Complex-Daejeon, 139 Seonsa-ro, Seo-  
gu, Daejeon 302-701, Republic of Korea

Facsimile No. 82-42-472-7140

Authorized officer

KIM Jong Kee

Telephone No. 82-42-481-8301



**INTERNATIONAL SEARCH REPORT**

Information on patent family members

International application No.

**PCT/KR2007/006704**

| Patent document<br>cited in search report | Publication<br>date | Patent family<br>member(s)                                                   | Publication<br>date                                  |
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| JP 2007-073103 A                          | 22.03.2007          | None                                                                         |                                                      |
| US 2006/0108655 A1                        | 25.05.2006          | None                                                                         |                                                      |