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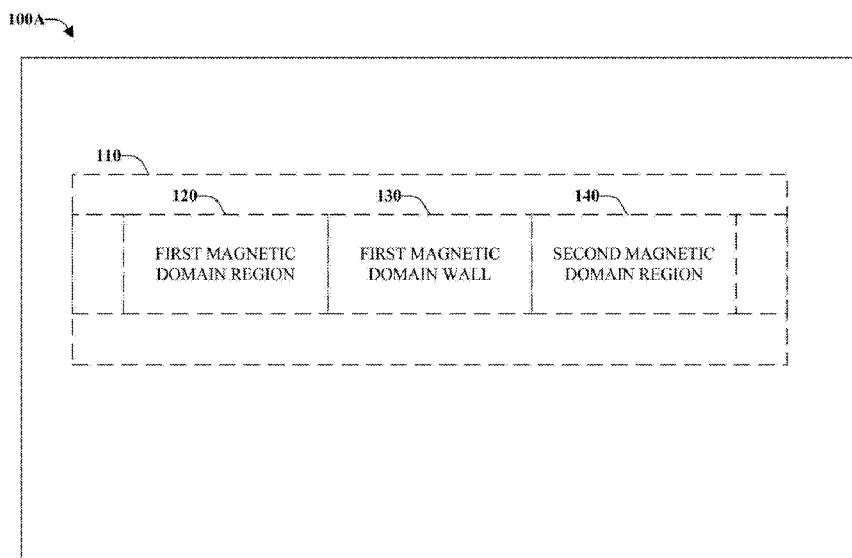


FIG. 1(A)

(57) **Abstract:** Disclosed herein are devices (100A), systems, and methods for selecting domain walls (130) of desired types in a magnetic nanowire (110) by pinning and depinning domain walls (130) in the vicinity of notches (150), anti-notches (160) and defects within the magnetic nanowire (110). Furthermore, in an aspect, one or more magnetic domain walls (130) associated with respective chiralities or polarities can be created by pinning or depinning one or more locations of a magnetic nanowire (110). In another aspect, information can be stored on a storage device based on the pinning or depinning of domain walls (130) and the respective chiralities or polarities associated with the domain walls (130) respectively.



MAGNETIC DOMAIN WALL FILTERS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to United States Provisional Application Number 61/967,809, filed March 27, 2014, and entitled “MAGNETIC DOMAIN WALL FILTERS”, the entirety of which is expressly incorporated herein by reference.

TECHNICAL FIELD

[0002] This disclosure relates to systems, methods, and devices capable of selecting, confining, depinning, and controlling domain walls and domain wall boundaries.

BACKGROUND

[0003] As computer technologies continue to advance and innovate, there is a growing need to improve computer related processes such as collecting, storing, and retrieving data or information. A technology that holds potential to achieving such computer process goals rests with an emerging technology known as spintronics. Spintronics is a technology that aims to improve logic circuits, data storage, and data retrieval. Unlike conventional electronic devices, which rely on electron charge properties to carry electrical charge, a spintronic device can exploit the intrinsic spin of an electron, the magnetic moment of an electron, and the electronic charge properties of an electron to improve memory storage technologies, magnetic sensor applications, logic circuits, quantum computing, and a range of other technology applications.

[0004] Although, spintronic devices make use of a spin of an electron to facilitate information processing, such electron spin is not conserved as compared to the charge of an electron. Thus, there is currently a need to identify methods, systems, and devices, capable of manipulating electron spins in order to improve information processing techniques and other spintronic based technology applications. Furthermore, there is a need to identify methods, systems, and devices capable of manipulating and controlling the magnetic domain wall qualities associated with spintronic devices.

SUMMARY

[0005] The following presents a simplified summary of the disclosure in order to provide a basic understanding of some aspects of the disclosure. This summary is not an extensive overview of the disclosure. It is intended to neither identify key or critical elements of the disclosure nor delineate any scope of particular embodiments of the disclosure, or any scope of the claims. Its sole purpose is to present some concepts of the disclosure in a simplified form as a prelude to the more detailed description that is presented later.

[0006] In accordance with one or more embodiments and corresponding disclosure, various non-limiting aspects are described in connection with systems and methods for selecting, pinning, and depinning domain walls. In an embodiment, a device is provided comprising a first magnetic domain region, a second magnetic domain region, and a first magnetic domain wall. In an aspect, the first magnetic domain region comprises a first set of atoms magnetized toward a first direction relative to being non-magnetized. In another aspect, the second magnetic domain region comprises a second set of atoms magnetized toward a second direction relative to being non-magnetized, wherein the second direction is opposite to the first direction. In yet another aspect, the first magnetic domain wall separates the first magnetic domain region and the second magnetic domain region, wherein the first magnetic domain wall is located between the first magnetic domain region and the second magnetic domain region, and wherein the first magnetic domain wall is located within a first notch, a first anti-notch, or a first defect of a magnetic nanowire.

[0007] In another embodiment, a method is provided comprising selecting, by a device, a set of magnetic domain walls within a magnetic nanowire, wherein the magnetic nanowire comprises a first set of objects corresponding to the set of magnetic domain walls, and wherein the first set of objects comprise at least one of a notch, an anti-notch, or a defect. In another aspect, the method comprises applying, by the device, a first magnetic field to the magnetic nanowire at a first location of a first subset of magnetic domain walls of the set of magnetic domain walls, wherein the first magnetic field corresponds to a first field strength value, and wherein the first subset of magnetic domain walls comprises a first domain wall size.

[0008] The following description and the annexed drawings set forth certain illustrative aspects of the disclosure. These aspects are indicative, however, of but a few of the various ways in which the principles of the disclosure may be employed. Other aspects of the disclosure will become apparent from the following detailed description of the disclosure when considered in conjunction with the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIG. 1(A) illustrates an example non-limiting device that contains a magnetic domain wall within a magnetic nanowire.

[0010] FIG. 1(B) illustrates an example non-limiting device that contains a magnetic domain wall within a notch in a magnetic nanowire.

[0011] FIG. 1(C) illustrates an example non-limiting device that contains a magnetic domain wall within an anti-notch in a magnetic nanowire.

[0012] FIG. 1(D) illustrates an example non-limiting device that contains a magnetic domain wall within a defect in a magnetic nanowire.

[0013] FIG. 2(A) illustrates an example non-limiting device that contains an anticlockwise magnetic domain wall within a notched magnetic nanowire.

[0014] FIG. 2(B) illustrates an example non-limiting device that contains a clockwise magnetic domain wall within a notched magnetic nanowire.

[0015] FIG. 2(C) illustrates an example non-limiting device that contains an anticlockwise magnetic domain wall within an anti-notched magnetic nanowire.

[0016] FIG. 2(D) illustrates an example non-limiting device that contains a clockwise magnetic domain wall within an anti-notched magnetic nanowire.

[0017] FIG. 3(A) illustrates an example non-limiting magnetic domain structure in a notched magnetic nanowire.

[0018] FIG. 3(B) illustrates an example non-limiting magnetic domain wall generation in a notched magnetic nanowire comprising an anticlockwise transverse magnetic domain wall.

[0019] FIG. 3(C) illustrates another example non-limiting magnetic domain wall generation in a notched magnetic nanowire comprising a clockwise transverse magnetic domain wall.

[0020] FIG. 3(D) illustrates an example non-limiting magnetic domain wall pinning in a notched magnetic nanowire comprising an anticlockwise transverse magnetic domain wall pinned at the notch.

[0021] FIG. 3(E) illustrates another example non-limiting magnetic domain wall pinning in a notched magnetic nanowire comprising a clockwise transverse magnetic domain wall pinned at the notch.

[0022] FIG. 4 illustrates an example non-limiting graph plotting the depinning field strength of a magnetic domain wall as a function of a triangular notch's depth for an anticlockwise domain wall and a clockwise domain wall.

[0023] FIG. 5 illustrates an example non-limiting graph plotting the depinning field strength of a magnetic domain wall as a function of a triangular anti-notch's depth for an anticlockwise domain wall and a clockwise domain wall.

[0024] FIG. 6 illustrates an example non-limiting domain wall filter device that selects anticlockwise domain walls and pins clockwise domain walls.

[0025] FIG. 7 illustrates an example non-limiting domain wall filter device that selects clockwise domain walls and pins anticlockwise domain walls.

[0026] FIG. 8 illustrates an example non-limiting example methodology for selecting, pinning, and depinning magnetic domain walls within a magnetic nanowire.

[0027] FIG. 9 illustrates another example non-limiting example methodology for selecting, pinning, and depinning magnetic domain walls within a magnetic nanowire.

[0028] FIG. 10 illustrates another example non-limiting example methodology for selecting, pinning, and depinning magnetic domain walls within a magnetic nanowire.

DETAILED DESCRIPTION

OVERVIEW

[0029] The various embodiments are now described with reference to the drawings, wherein like reference numerals are used to refer to like elements throughout. In the following description, for purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the various embodiments. It may be evident, however, that the various embodiments can be practiced without these specific details. In other instances, well-known structures and components are shown in block diagram form in order to facilitate describing the various embodiments.

[0030] By way of introduction, this disclosure relates to spintronic methods, systems, and devices that make use of notches, anti-notches, or defects of a nanowire to select domain walls. Furthermore, the methods, systems, and devices disclosed herein describe selecting, pinning and depinning domain walls within a nanowire. In an aspect, a spintronic device can rely on the spin of an electron, in addition to the charge of an electron, to store and transport information. This mechanism facilitates the creation of smaller, versatile, and robust devices that act according to a spin-based information storage and transport mechanism as opposed to traditional semiconductor devices, silicon chips and circuit elements that act according to a charge-based information storing and transport mechanism.

[0031] A spintronic device can store or write information into spins of an electron, specifically a particular orientation of a spin, such as an “up” orientation or “down” orientation, where each respective orientation can be used to store particular information. The spins are characteristics of electrons and the electrons carry the stored information along a wire or a nanowire. Furthermore, the stored information can be read at a given terminal or point of connection to an external circuit. A spintronic device can utilize the concept of an on/off switch such that locations along the wire or nanowire that present a sufficient or insufficient spin measurement can be associated with an ‘on’ or ‘off’ function respectively. The capability of storing information in association with such an on/off mechanism facilitates the use of spintronic devices in processing binary logic computations. This disclosure describes methods, systems, and devices capable of manipulating the spin directions or spin measurements of electrons within a wire or nanowire. As such the devices can provide benefits such as providing faster computational speeds, low power consumption, and compact device designs. Furthermore, devices based on manipulating and sensing the spin and charge of electrons within a nanowire offer advantages such as high density, high speed, and non-volatility.

[0032] The spintronic device disclosed herein utilizes various notches, anti-notches and defects on an otherwise homogeneous nanowire to select one or more desired type of magnetic domain walls. The desired domain wall acts as a transitional region connecting magnetic domains with different magnetization directions respectively. The device can also transmit domain walls along a nanowire by applying magnetic fields in the nanowire. As such the domain walls can be pinned in the vicinity of artificial notches,

anti-notches, or defects within an otherwise homogeneous magnetic nanowire. Each domain wall may be associated with a large difference in depinning fields from another domain wall depending on the geometry of the magnetic nanowire, notch, anti-notch, or defect.

[0033] The device can utilize the sufficiently large differences in depinning fields to construct, select, and purify domain walls such that various domain walls can be pinned or depinned within a given magnetic nanowire. Therefore, by applying fields with respective values to magnetic nanowires comprising notches, anti-notches, and defects of a particular geometry, desired domain walls can be selected, pinned, depinned and purified using the disclosed device. Furthermore, the disclosed device can generate and select magnetic domain walls that possess a particular chirality. In an aspect, the device can be utilized with racetrack memory technologies that require domain walls to store information. Furthermore, in an aspect, the device can be utilized by magnetic logic gates that require different domain walls to mimic logic gates and utilize magnetic domain wall filters to achieve such goals. Also, domain wall filters using a pinning effect offers numerous technological advancements in connection with existing technologies.

EXAMPLES

[0034] Disclosed herein are systems and methods for hiding data within videos and images in an unobstructive and invisible manner to users. Referring initially to FIG. 1A, a spintronic device 100A is illustrated. In an aspect, device 100A comprises a first magnetic domain region 120 comprising a first set of atoms magnetized toward a first direction relative to being non-magnetized; a second magnetic domain region 140 comprising a second set of atoms magnetized toward a second direction relative to being non-magnetized, wherein the second direction is opposite to the first direction; and a first magnetic domain wall 130 that separates the first magnetic domain region 120 and the second magnetic domain region 140, wherein the first magnetic domain wall 130 is located between the first magnetic domain region 120 and the second magnetic domain region 140, and wherein the first magnetic domain wall 130 is located within a first notch, a first anti-notch, or a first defect of a magnetic nanowire 110.

[0035] In an aspect, the device 100A comprises a first magnetic domain region 120 within a magnetic nanowire 110. In an aspect, magnetic nanowire 110 is a material

with a high length to width ratio where the width can be below several hundred nanometers and or as small as several nanometers. Furthermore, magnetic nanowire 110 can possess a high aspect ratio and high surface area to volume ratio. Also, magnetic nanowire 110 can comprise a material selected from a group consisting of a magnetic metal material, a magnetic semiconductor material, and a magnetic insulator material. The magnetic properties or exhibited behaviors of magnetic nanowire 110 can include those associated with ferromagnetic materials.

[0036] In an aspect, within magnetic nanowire 110 are one or more domain regions such as first magnetic domain region 120. A magnetic domain represents a region of uniform magnetization in ferromagnetic materials. Within each magnetic domain region, the magnetizations of the electrons within such region are aligned in a single direction. A domain wall, such as first magnetic domain wall 130 is the transitional region between each magnetic domain region (e.g., regions of uniform magnetization). Thus a magnetic domain wall is an interface where different magnetic directions associated with different magnetic domain regions meet. In an aspect, this disclosure describes a spintronic device capable of generating, confining, controlling, and accurately positioning in accordance with demand functions, one or more magnetic domain walls. Accordingly, the magnetic domain walls can be utilized in various applications including data storage, data retrieval, and logic operations via the spintronic devices.

[0037] In an aspect, propagation of magnetic domain walls at various locations within a nanowire can be achieved by applying magnetic fields in the nanowire. Furthermore, domain walls can be pinned at various sites along the nanowire using artificial notches, anti-notches and defects within otherwise homogenous nanowires.

[0038] In an aspect, a magnetic domain wall can be moved out of a notch, anti-notch, or defect where an external field is applied in the magnetic nanowire associated with a notch, an anti-notch, or a defect. The minimum field required to move a domain wall out of notches, anti-notches and defects is referred to as the depinning field. In an aspect, the depinning field represents the pinning strength of a domain wall in a notched, anti-notched, or defected nanowire. Furthermore, the strength of the depinning field depends on the geometry of the nanowire and notch or anti-notch geometry as well as the type of magnetic domain wall present within the magnetic nanowire.

[0039] In an aspect, device 100A comprises a first magnetic domain region 120 comprising a first set of atoms magnetized toward a first direction relative to being non-magnetized. Device 100A also comprises a second magnetic domain region 140 comprising a second set of atoms magnetized toward a second direction relative to being non-magnetized, wherein the second direction is opposite to the first direction. Device 100A further comprises a first magnetic domain wall 130 that separates the first magnetic domain region 120 and the second magnetic domain region 140, wherein the first magnetic domain wall 130 is located between the first magnetic domain region 120 and the second magnetic domain region 140, and wherein the first magnetic domain wall 130 is located within a first notch, a first anti-notch, or a first defect of a magnetic nanowire 110. For instance, device 100A can comprise a first magnetic domain wall 130 pinned by a notch where the first magnetic domain wall 130 is a clockwise transverse wall. Furthermore, the atoms within the first magnetic domain region 120 can flow from a westward direction to an eastward direction and the atoms within the second magnetic domain region 140 can flow from an eastward direction to a westward direction.

[0040] Turning now to FIG.'s 1(B)-(D), illustrated are non-limiting examples of devices 100B, which illustrate various types of domain walls pinned within notches, anti-notches, and defects in nanowires. In an aspect, at FIG. 1(B), illustrated is a first magnetic domain region 120 comprising a first set of atoms 152 magnetized toward a first direction relative to being non-magnetized. In another aspect, illustrated is a second magnetic domain region 140 comprising a second set of atoms magnetized toward a second direction 154 relative to being non-magnetized, wherein the second direction is opposite to the first direction. In another aspect, a first magnetic domain wall 130 separates the first magnetic domain region 120 and the second magnetic domain region 140, wherein the first magnetic domain wall 130 is located between the first magnetic domain region 120 and the second magnetic domain region 140, and wherein the first magnetic domain wall 130 is located within a first notch 150 of a magnetic nanowire 110.

[0041] In another aspect, at FIG. 1(C), illustrated is a first magnetic domain region 120 comprising a first set of atoms 152 magnetized toward a first direction relative to being non-magnetized. In another aspect, illustrated is a second magnetic domain region 140 comprising a second set of atoms magnetized toward a second direction 154 relative to being non-magnetized, wherein the second direction is opposite to the first

direction. In another aspect, a first magnetic domain wall 130 separates the first magnetic domain region 120 and the second magnetic domain region 140, wherein the first magnetic domain wall 130 is located between the first magnetic domain region 120 and the second magnetic domain region 140, and wherein the first magnetic domain wall 130 is located within a first anti-notch 160 of a magnetic nanowire 110.

[0042] In yet another aspect, at FIG. 1(D), illustrated is a first magnetic domain region 120 comprising a first set of atoms 152 magnetized toward a first direction relative to being non-magnetized. In another aspect, illustrated is a second magnetic domain region 140 comprising a second set of atoms magnetized toward a second direction 154 relative to being non-magnetized, wherein the second direction is opposite to the first direction. In another aspect, a first magnetic domain wall 130 separates the first magnetic domain region 120 and the second magnetic domain region 140, wherein the first magnetic domain wall 130 is located between the first magnetic domain region 120 and the second magnetic domain region 140, and wherein the first magnetic domain wall 130 is located within a first defect 170 of a magnetic nanowire 110.

[0043] Turning now to FIG's. 2(A)-(D), illustrated are non-limiting examples of devices 200 that illustrate various types of domain walls pinned within nanowires by notches and anti-notches. Also demonstrated are the effects of magnetic domain wall pinning (e.g., using magnetic domain wall 130) within magnetic nanowires (e.g., using magnetic nanowire 110). At FIG. 2(A), illustrated is a magnetic nanowire comprising a pinned magnetic domain wall 202 in the vicinity of a triangular notch 204. Furthermore, the nanowire is connected to a pad where magnetic domain wall 202 is initially generated and then moved to the vicinity of triangular notch 204 by applying a weak magnetic field in the magnetic nanowire. In an aspect, magnetic domain wall 202 can be created in the pad and then moved to the notch region. At FIG. 2(A), magnetic domain wall 202 is transverse to the magnetic nanowire and is pinned by triangular notch 204. At FIG. 2(B), magnetic domain wall 202 is transverse to the magnetic nanowire and is pinned by triangular notch 204. At FIG. 2(C), magnetic domain wall 202 is transverse to the magnetic nanowire and is pinned by a triangle anti-notch 206. At FIG. 2(D), magnetic domain wall 202 is transverse to the magnetic nanowire and is pinned by a triangular anti-notch 206.

[0044] Referring to FIG. 3(A)-(E), illustrated are non-limiting example devices 300 for pinning magnetic domain walls within nanowires by notches and anti-notches. The transverse domain walls having different chiralities are produced from the same initial state of the magnetic nanowire in FIG. 3(A) via the same process (e.g., applying a magnetic field to the magnetic nanowire). In an aspect, the device can generate magnetic domain walls of different chiralities. In another aspect, a magnetic nanowire with a desired type of magnetic domain wall cannot be achieved unless the use of a spintronic device which is capable of selecting and purifying domain walls. This is the concern of magnetic domain wall filters.

[0045] At FIG. 3(A), illustrated is a basic structure of a magnetic domain wall filter comprising a pad 302 and a notch 304 within a notched magnetic nanowire. Several types of magnetic domain walls (e.g., clockwise, anticlockwise) can be generated from the same pad. The magnetic nanowire can be visualized along a horizontal x-axis (e.g., magnetic nanowire thickness), vertical, y-axis (e.g., width), and z-axis (e.g., length). In an aspect, a large magnetic field can be applied in the magnetic nanowire in a manner that saturates the magnetic nanowire in the negative z-axis. FIG. 3(A) illustrates such an application of a magnetic field, which generates a single domain with magnetization in pad 302 and magnetic nanowire along the negative z-axis. Magnetic domain walls are fundamental structures in spintronic devices. As such, the disclosed devices and various non-limiting embodiments can be implemented with domain wall devices such as racetrack memory, shift register, vortex memory where the chirality or polarity of a magnetic domain wall is used as binary bits. The disclosed magnetic domain wall filter can supply desired types of domain walls for such domain wall dependent devices.

[0046] At FIG. 3(B), illustrated is a magnetic nanowire comprising an anticlockwise transverse magnetic domain wall. A weak magnetic field is applied to the magnetic nanowire along the positive z-axis direction of the magnetic nanowire. Accordingly, the magnetic moments in pad 302 are inverted slowly due to the shape anisotropy of pad 302 being weaker than that of the magnetic nanowire. After all the magnetic moments in pad 302 are inverted to the direction of the x-axis, a head-to-head magnetic domain wall is created in the magnetic nanowire. At FIG. 3(C), illustrated is the creation of a clockwise transverse magnetic domain wall created from the pad structure illustrated at FIG. 3(A). At FIG. 3(D), illustrated is the creation of an

anticlockwise transverse magnetic domain wall created from the pad structure illustrated at FIG. 3(A). At FIG. 3(E), illustrated is the creation of a clockwise transverse magnetic domain wall created from the pad structure illustrated at FIG. 3(A). In an aspect, a head-to-head magnetic domain wall can be created but chirality may be uncertain (as shown in FIG. 3(D) and 3(E). In another aspect, a tail-to-tail domain wall can also be produced from the same magnetic nanowire illustrated at FIG. 3A by changing directions of the applied fields and accordingly two chiralities can appear.

[0047] In an aspect, the disclosed device is capable of generating several types of magnetic domain walls from a source connected to a nanowire. Each type of magnetic domain wall is pinned by a notch, anti-notch, or defect and the depinning strength of the domain walls can be different from one another as examined numerically. A magnetic field can be applied in a nanowire and move the domain wall out of a notch, anti-notch, or defect if such applied field is larger than the depinning field of the respective domain wall. Thus, when a magnetic field is applied in the magnetic nanowire, the respective domain walls with associated depinning fields that are smaller than the applied magnetic field will move out of a notch, anti-notch or defect of the magnetic nanowire whereas those magnetic domain walls with depinning fields greater than the applied magnetic field will remain pinned.

[0048] In another aspect, the depinning strength of each type of domain wall depends on the geometry of the notch, anti-notch or defect and the structure of the magnetic nanowire. Consequently, an applied field can move various domain wall types out of a magnetic nanowire with a particular notch or anti-notch geometry. Similarly, various types of domain walls can also be pinned by notches, anti-notches, or defects of a magnetic nanowire. In an aspect, the Landau-Lifshitz-Gilbert (LLG) equation was solved numerically to verify the method of pinning and depinning of domain walls within a nanowire. A magnetic nanowire is considered with length l_z , width l_y and thickness l_x with a triangular notch (anti-notch) of width w and depth d located at the upper edge, which is connected to a rectangle pad at an end. At FIG. 3(A) the top view of the device is presented.

[0049] The dynamics of the magnetization is governed by the LLG equation

$$\frac{\partial \mathbf{m}}{\partial t} = -\gamma \mathbf{m} \times \mathbf{H}_{eff} + \alpha \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t}$$

Here $\mathbf{m}$ is the normalized vector of local magnetization $\mathbf{M}=M_s\mathbf{m}$ where M_s is the saturation magnetization, γ is the gyromagnetic ratio, α is the phenomenological Gilbert damping constant, and $\mathbf{H}_{\text{eff}}$ is the effective field including the exchange field $\mathbf{H}_{\text{ex}} = 2A\nabla^2\mathbf{m}$, the anisotropy field $\mathbf{H}_{\text{an}}$, the demagnetizing field $\mathbf{H}_d$ and the external field $\mathbf{H}_{\text{ext}}$, namely $\mathbf{H}_{\text{eff}} = \mathbf{H}_{\text{ex}} + \mathbf{H}_{\text{an}} + \mathbf{H}_d + \mathbf{H}_{\text{ext}}$.

[0050] The analytical integration of the LLG equation is challenging due to the presence of nonlinear characters in exchange field. Therefore, suitable numerical methods are needed to solve the equation. In an aspect, the Object Oriented Micro Magnetic Framework (OOMMF) package is used to simulate the magnetization dynamics. The parameters are set as $A = 1.3 \times 10^{-11} \text{ J/m}$, $M_s = 8 \times 10^5 \text{ A/m}$, α is set to 0.1. The simulation assumes that all the nanowires are 1000 nm long, 64 nm wide and 4 nm thick. The isosceles triangular notch or triangular anti-notch is 64 nm wide and its depth varies as needed. Here we restrict the notch depth to be less than 60% of the nanowire width so as to avoid the possible new magnetic domain wall nucleation near the notch edge.

[0051] In an aspect, the state after domain wall creation is a domain wall pinned in the vicinity of the notches as illustrated in FIG's. 2(A)-(D), which can be produced by firstly generating a magnetic domain wall in the pad and then moving it to the notch under a weak applied field. In order to determine the depinning field, an external field is applied along the positive z-axis of the magnetic nanowire and the external field is increased at a step of 5 Oersted (Oe) to push the magnetic domain wall out of the notch. The minimum field required to release the domain wall is referred to as the depinning field.

[0052] Referring now to FIG's 4 and 5, illustrated is a depinning field as a function of a triangular notch's depth as relates to a clockwise and an anticlockwise magnetic domain wall. As previously described herein, the depinning field strongly depends on the magnetic nanowire and notch or anti-notch geometry and the magnetic domain wall type. The above-described equations explain numerically how the depinning fields vary with the chiralities of head-to-head transverse walls and shapes of notches, anti-notches and defects within the magnetic nanowire. In an aspect, FIG. 4 illustrates a graph 400 plotting the depinning field strength of a magnetic domain wall as a function of a triangular notch's depth (in nm) for an anticlockwise wall (dots) and a clockwise

wall (crosses). The depinning field strength of a clockwise wall is larger than that of an anticlockwise wall and their difference can reach about 65 Oe. In another aspect, FIG. 5 illustrates a graph 500 plotting the depinning field strength as a function of an anti-notch's depth for an anticlockwise domain wall (e.g., illustrated as dots) and a clockwise domain wall (e.g., illustrated as crosses). For the notch depth larger than 16 nm, the depinning field of an anticlockwise wall begins to surpass that of a clockwise wall and their difference could reach 80 Oe when the notch depth is 32 nm. The difference between the depinning fields of the two types of domain walls provides the basis for designing delicate devices to select desired domain wall types.

[0053] Referring to FIG. 6, illustrated is a device 600 that selects domain walls 606. In an aspect, the clockwise anticlockwise magnetic domain walls can be selected and pinned by a first notch 602 or second anti-notch 604, which is based on different depinning fields of an anticlockwise wall and a clockwise wall, and also different depinning fields of a notch and an anti-notch respectively. The nanowire dimensions are 64 nm wide, 4 nm thick and of sufficient length. The first triangular notch is 64 nm wide and 16 nm deep while the second triangular notch is 64 nm wide and 32 nm deep. Its working process is illustrated in the following.

[0054] Beginning at the pad on the left hand side of the nanowire, both an anticlockwise wall and a clockwise wall can be produced. Once the domain wall is generated, a weak magnetic field along the longitudinal direction of the magnetic nanowire is applied to push the magnetic domain wall to propagate towards the first notch, and the magnetic domain wall is easy to be pinned by the notch since the applied field is quite small. Once the magnetic domain wall is pinned, the small field is switched off and another applied with a field value of 100 Oe is switched on. The magnetic nanowire and notch geometry are chosen delicately based on the depinning fields of an anticlockwise wall (75 Oe) is sufficient smaller than that of a clockwise wall (135 Oe). The applied field (100 Oe) is between the two depinning fields. Therefore, only the generated anticlockwise wall could move out of the notch and the clockwise wall will be pinned still. In an aspect, the anti-notch, whose geometry is chosen properly, is designed to render the coming anticlockwise wall pinned. Such design can be substituted by those devices that need to make use of anticlockwise walls.

[0055] Referring to FIG. 7, illustrated is a device 700 to capture clockwise magnetic domain walls 706. In an aspect, the device can select a clockwise magnetic domain wall by modifying the geometry of the magnetic nanowire or elements of the magnetic nanowire such as notches 704, anti-notches 702, or defects. In another aspect, the magnetic nanowire dimensions such as width, thickness, and notch size can remain the same, however the positions of the notch and anti-notch can be switched (as compared to the positions of the notch and anti-notch in FIG. 6). Again, a weak field can be applied in the magnetic nanowire to pin the magnetic domain wall near the notch and anti-notch. In an aspect, another magnetic field of 100 Oe can be applied to the magnetic nanowire, which can generate a clockwise magnetic domain wall that passes the first notch and keeps propagating until pinned by the second notch. The depinning field of the anticlockwise wall (e.g., 130 Oe) is larger than the applied field (e.g., 100 Oe) and the depinning field (50 Oe) of a clockwise wall, which is smaller than the applied field. In an aspect, the geometry of a second notch of the magnetic nanowire is selected such that the depinning field of a clockwise wall is 190 Oe, which is sufficiently larger than the applied field (100 Oe) and consequently, the selected clockwise wall can be pinned by the second notch.

[0056] In an instance, a magnetic nanowire comprising triangular notches is taken as an example to describe device 700 capable of selecting magnetic domain walls. The physics principle associated with such device can be generalized to apply to other types of notch structures and complex magnetic domain wall types such as vortex and anti-vortex magnetic domain walls. Furthermore, as a nanowire becomes wider and thicker, the possible varieties of magnetic domain walls become more abundant. Accordingly, in such wider and thicker magnetic nanowires, there is a greater need to select desired types of magnetic domain walls.

[0057] In a non-limiting implementation of the device 700, the device 700 can firstly identify the possible magnetic domain wall types in a notchless specified magnetic nanowire. In an aspect, an anisotropy magnetoresistance (AMR) measurement can achieve a notchless magnetic nanowire. In another aspect, the presence of different domain wall structures may correspond to different changes in resistance of the magnetic nanowire. The change in resistance of the magnetic nanowire can be measured when the resistance is generated in the pad of the device. For instance, a nanowire that observes

two kinds of changes in resistance can reasonably possess two kinds of domain walls within the magnetic nanowire.

[0058] In an aspect, the magnetized distribution of possible domain wall structures can be observed using magnetic force microscopy (MFM) or spin polarized low energy electron microscopy (SPLEEM). Once the domain walls are identified, a notch can be introduced within the nanowire. Furthermore, in an aspect, the depinning field of various magnetic domain walls within the magnetic nanowire can be examined to observe the dependence of the various domain walls on the notch geometry. In another aspect, a magneto-optic Kerr effect (MOKE) can be utilized to measure the depinning field. The MOKE process facilitates the observation of different Kerr signals associated with magnetic domain walls in a pinned state and magnetic domain walls in a depinned state.

[0059] In an aspect, the magnetic field can be applied externally in the magnetic nanowire starting at zero and slowly increased. A curve of the Kerr signals can be plotted and an observed sudden jump in the curve (sometimes referred to as a hysteresis loop) can be associated with a corresponding depinning of a magnetic domain wall and the critical field where the jump occurs can be recognized as the depinned field. In order to obtain an accurate value of the depinning field, the process can be repeated to arrive at an average field where the jump in the curve occurs. In another aspect, similar MOKE experiments can provide information such as the geometry of a notch or magnetic nanowire, the notch size, and the extent to which a depinning field depends on types of magnetic domain walls. In order to select a particular domain wall within the magnetic nanowire, a notch geometry can be utilized such that a depinning field of concern (H_c) is much smaller than that of other depinning fields of the magnetic nanowire. Accordingly, an external field slightly larger than the field value of the H_c and smaller than the other depinning fields can be applied to the magnetic nanowire to select the desired magnetic domain wall (e.g., the magnetic domain wall pinned with the smallest applied field). Thus, the disclosed device is capable of selecting particular domain walls for pinning or depinning.

[0060] In another aspect, the efficacy of the disclosed device 700 can be demonstrated by performing the following process which includes fabricating a magnetic nanowire using electron beam lithography and depositing the magnetic domain wall on a

Silicon 100 substrate by using a magnetron sputtering process. The fabricated nanowire can comprise one or more notches on the side of the wire. Furthermore, a magnetic field H_{sat} can be generated, where the magnetic field measures several thousands Oe along the longitudinal direction of the wire to saturate the magnetization. Next, with the H_{sat} turned off, a magnetic field H_{inj} can be applied in the magnetic nanowire to inject domain walls into the magnetic nanowire from the pad. Further, a magneto-optic Kerr effect (MOKE), an anisotropic magneto-resistance (AMR), and magnetic force microscopy (AFM) can be used to identify whether the domain walls (DW's) are generated successfully. Also, after turning off the magnetic field H_{inj} , an H_{prop} field can be applied to the working window of the magnetic domain wall filter and the MOKE signal can be measured at the second notch of the magnetic nanowire. If an abrupt jump in the signal is observed, the domain wall of the desired type is selected, otherwise the magnetic field can be repeatedly applied until a signal response of the MOKE measurement is observed. Furthermore, an MFM and AMR technique can be used to verify the domain wall states at the second notch.

[0061] Turning now to FIG's. 8-10, illustrated are methods or flow diagrams in accordance with certain aspects of this disclosure. While, for purposes of simplicity of explanation, the disclosed methods are shown and described as a series of acts, the disclosed subject matter is not limited by the order of acts, as some acts may occur in different orders and/or concurrently with other acts from that shown and described herein. For example, those skilled in the art will understand and appreciate that a method can alternatively be represented as a series of interrelated states or events, such as in a state diagram. Moreover, not all illustrated acts may be required to implement a method in accordance with the disclosed subject matter.

[0062] Referring now to FIG. 8, presented is a flow diagram of a non-limiting example of a method 800 to select a magnetic domain wall (e.g., using first magnetic domain wall 130) within a magnetic nanowire. At 802, a device selects a set of magnetic domain walls within a magnetic nanowire, wherein the magnetic nanowire comprises a first set of objects corresponding to the set of magnetic domain walls, and wherein the first set of objects comprise at least one of a notch, an anti-notch, or a defect. At 804, the device applies a first magnetic field to the magnetic nanowire at a first location of a first subset of magnetic domain walls of the set of magnetic domain walls, wherein the first

magnetic field corresponds to a first field strength value, and wherein the first subset of magnetic domain walls comprises a first domain wall size. In an aspect, the first domain wall size can be a width, height or other dimension of the magnetic domain wall affected by an applied field.

[0063] Referring now to FIG. 9, presented is a flow diagram of a non-limiting example of a method 900 to select a magnetic domain wall within a magnetic nanowire. At 902, a device selects a set of magnetic domain walls within a magnetic nanowire, wherein the magnetic nanowire comprises a first set of objects corresponding to the set of magnetic domain walls, and wherein the first set of objects comprise at least one of a notch, an anti-notch, or a defect. At 904, the device applies a first magnetic field to the magnetic nanowire at a first location of a first subset of magnetic domain walls of the set of magnetic domain walls, wherein the first magnetic field corresponds to a first field strength value, and wherein the first subset of magnetic domain walls comprises a first domain wall size. At 906, the device applies a first depinning field in the magnetic nanowire at the first location of the first subset of magnetic domain walls, wherein the first depinning field corresponds to a first depinning field strength value.

[0064] Referring now to FIG. 10, presented is a flow diagram of a non-limiting example of a method 1000 to select a magnetic domain wall within a magnetic nanowire. At 1000, a set of magnetic fields is applied in a magnetic nanowire. At 1002, a set of magnetic domain walls are created using a pad structure connected with the nanowire. At 1004, a set of magnetic domain walls are pinned using at least one of a notch, an anti-notch, or a defect within the magnetic nanowire. At 1006, a first magnetic field of the set of magnetic fields is applied between a first magnetic domain wall and a second magnetic domain wall of the set of magnetic domain walls. At 1008, a second magnetic field of the set of magnetic fields is applied between the second magnetic domain wall and a third magnetic domain wall of the set of magnetic domain walls.

CLAIMS

What is claimed is:

1. A device, comprising:
 - a first magnetic domain region comprising a first set of atoms magnetized toward a first direction relative to being non-magnetized;
 - a second magnetic domain region comprising a second set of atoms magnetized toward a second direction relative to being non-magnetized, wherein the second direction is opposite to the first direction; and
 - a first magnetic domain wall that separates the first magnetic domain region and the second magnetic domain region, wherein the first magnetic domain wall is located between the first magnetic domain region and the second magnetic domain region, and wherein the first magnetic domain wall is located within a first notch, a first anti-notch, or a first defect of a magnetic nanowire.
2. The device of claim 1, further comprising a source component configured to generate the first magnetic domain wall within the magnetic nanowire by application of a current or a magnetic field in the magnetic nanowire.
3. The device of claim 1, wherein the magnetic nanowire comprises a material comprising at least one of a magnetic metal material, a magnetic semiconductor material, or a magnetic insulating material.
4. The device of claim 2, wherein the magnetic domain wall is a Bloch wall, or a Néel wall.
5. The device of claim 1, wherein the first notch, the first anti-notch, and the first defect are any of a triangle, square, rectangle, sphere, or other irregular geometries.

6. The device of claim 5, wherein the first magnetic domain wall is associated with a first pinning field which is sufficient to pin the first magnetic domain wall within the first notch, the first anti-notch, or the first defect.

7. The device of claim 6, further comprising a pinning component that pins a second magnetic domain wall within a second notch, a second anti-notch or a second defect of the magnetic nanowire, wherein the second magnetic domain wall is associated with a second pinning field which is sufficient to pin the second magnetic domain wall within the second notch, the second anti-notch or the second defect of the magnetic nanowire.

8. The device of claim 7, further comprising a depinning component that changes a first size of the first magnetic domain wall or a second size of the second magnetic domain wall by application of a first depinning field comprising a first depinning strength to a first location of the magnetic nanowire, wherein the first depinning strength is greater than the first pinning strength or the second pinning strength.

9. The device of claim 8, wherein the depinning component changes the first size of the first magnetic domain wall and the second size of the second magnetic domain wall by application of the first depinning field to the first location of the magnetic nanowire and a second depinning field comprising a second depinning strength to a second location of the magnetic nanowire, wherein the first depinning strength and the second depinning strength are greater than the first pinning strength and the second pinning strength respectively, and wherein the first de-pinning strength is different than the second de-pinning strength.

10. The device of claim 7, wherein the second notch, the second anti-notch, and the second defect have respective second shapes that are different than respective first shapes of the first notch, the first anti-notch, and the first defect.

11. A method, comprising:

selecting, by a device, a set of magnetic domain walls within a magnetic nanowire, wherein the magnetic nanowire comprises a first set of objects corresponding to the set of magnetic domain walls, and wherein the first set of objects comprise at least one of a notch, an anti-notch, or a defect; and

applying, by the device, a first magnetic field in the magnetic nanowire at a first location of a first subset of magnetic domain walls of the set of magnetic domain walls, wherein the first magnetic field corresponds to a first field strength value, and wherein the first subset of magnetic domain walls comprises a first domain wall size.

12. The method of claim 11, further comprising, by the device, a first depinning field in the magnetic nanowire at the first location of the first subset of magnetic domain walls, wherein the first depinning field corresponds to a first depinning field strength value.

13. The method of claim 12, wherein the first depinning field strength value is greater than the first field strength value, and wherein the first domain wall size changes in size based on a difference in magnitude between the first depinning field strength value and the first field strength value.

14. The method of claim 12, wherein the first field strength value has a greater strength value than the first depinning field strength value that opposes the first depinning field strength value.

15. The method of claim 12, further comprising:

applying, by the device, a second magnetic field to the magnetic nanowire at a second location of a second subset of magnetic domain walls of the set of magnetic domain walls, wherein the second magnetic field corresponds to a second field strength value, and wherein the second subset of magnetic domain walls comprises a second domain wall size; and

applying, by the device, a second depinning field to the magnetic nanowire at the second location of the second subset of magnetic domain walls, wherein the second depinning field corresponds to a second depinning field strength value.

16. The method of claim 15, wherein the first depinning field strength value is greater than the first field strength value,

wherein the first domain wall size changes in size based on a first difference in magnitude between the first depinning field strength value and the first field strength value, and

wherein the second field strength value has a greater strength value than the second de-pinning field strength value that opposes the second field strength value.

17. The method of claim 12, wherein the notch, the anti-notch, and the defect correspond to a set of triangle notch shapes, a set of triangle anti-notch shapes, and a set of triangle defect shapes respectively, and wherein a geometry of the magnetic nanowire comprises any combination of the set of triangle notch shapes, the set of triangle anti-notch shapes or the set of triangle defect shapes.

18. A method, comprising:
- applying a set of magnetic fields in a pad connected to a magnetic nanowire;
 - pinning a first magnetic field of the set of magnetic fields within a first notch, a first anti-notch, or a first defect of the magnetic nanowire, wherein a first pinning of the first magnetic field creates a first magnetic domain wall;
 - pinning a second magnetic field of the set of magnetic fields within a second notch, a second anti-notch, or a second defect of the magnetic nanowire, wherein a second pinning of the second magnetic field creates a second magnetic domain wall; and
 - storing information at a storage device based on a chirality or a polarity associated with the first domain wall, the second domain wall, or the third domain wall.
19. The method of claim 18, wherein a set of atoms within the magnetic nanowire spin in a clockwise rotation or an anticlockwise rotation.
20. The method of claim 19, wherein a first subset of atoms of the set of atoms within the first magnetic domain wall rotate in a first direction based on a first collective spin of the first subset of atoms, and wherein a second subset of atoms of the set of atoms within the second magnetic domain wall rotate in a second direction based on a second collective spin of the second subset of atoms.

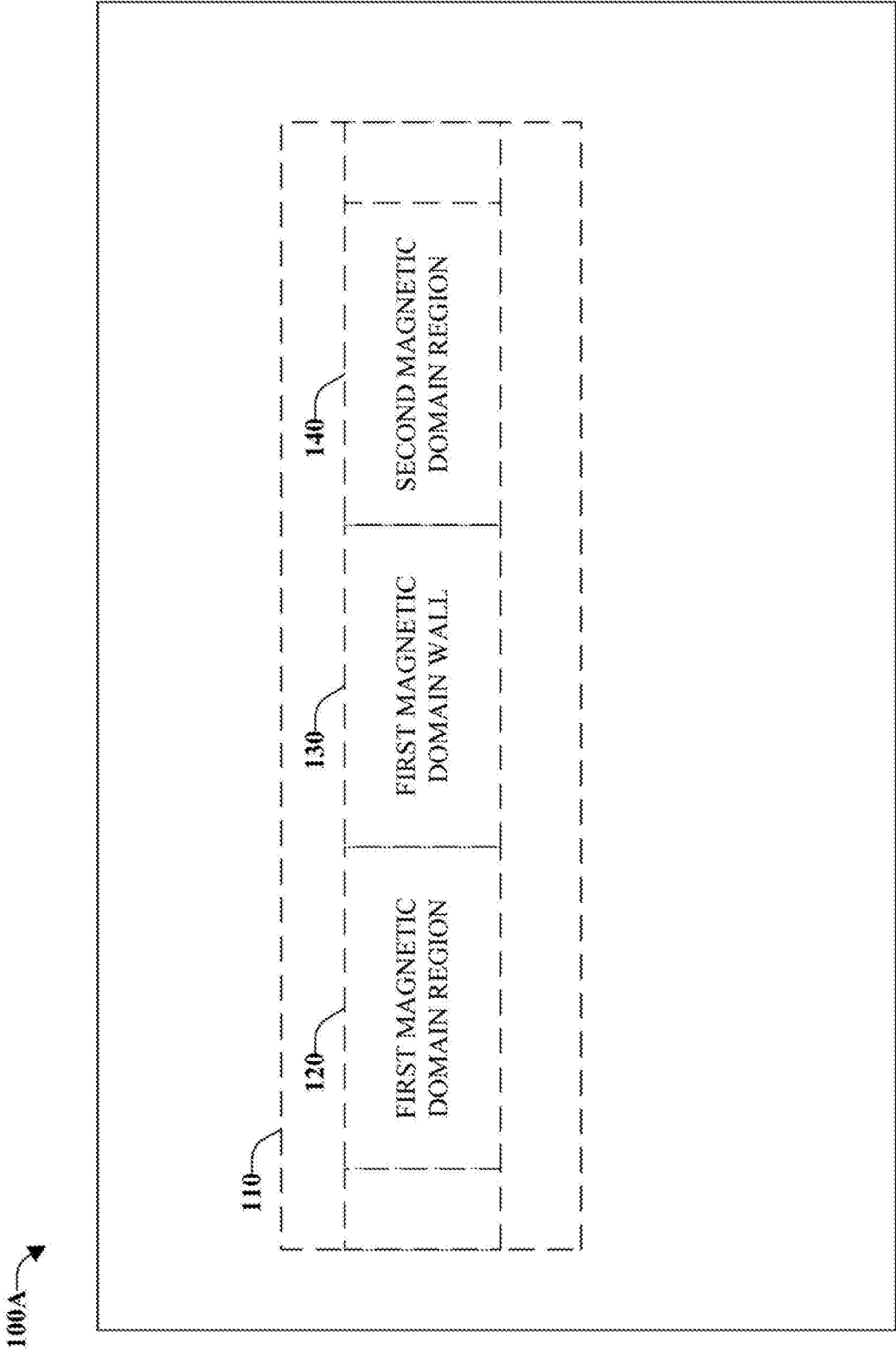


FIG. 1(A)

100B

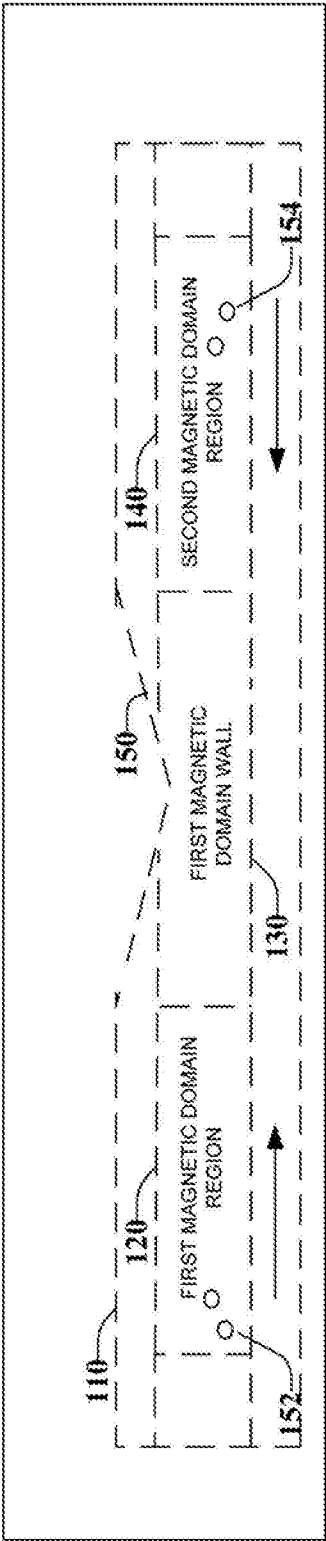


FIG. 1(B)

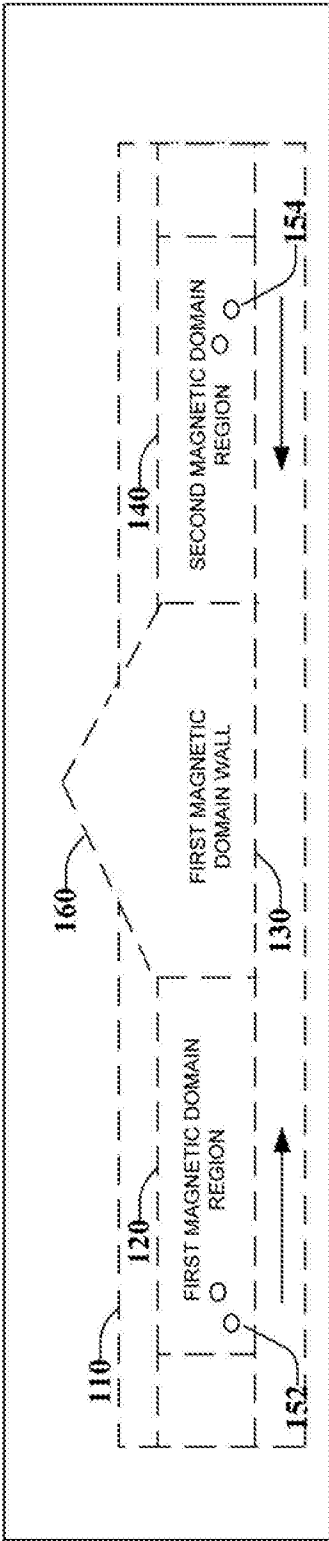


FIG. 1(C)

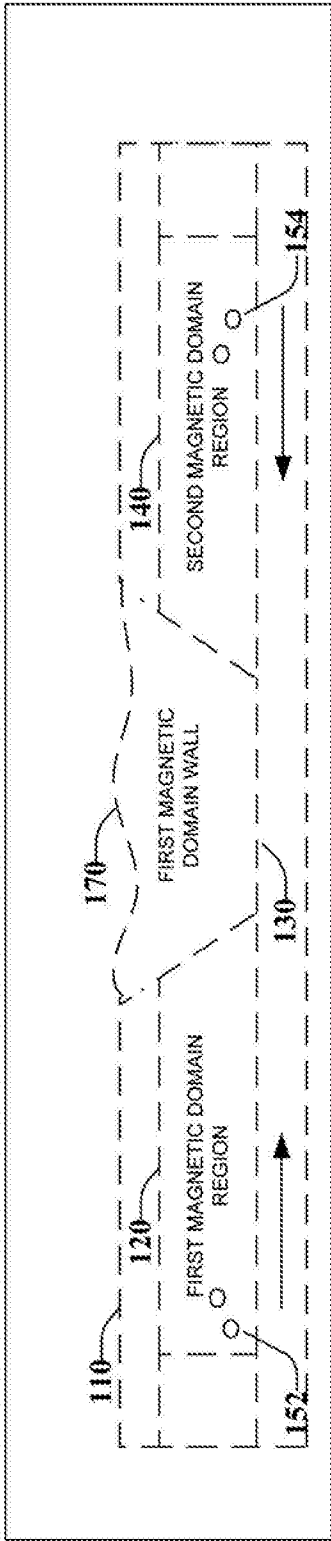


FIG. 1(D)

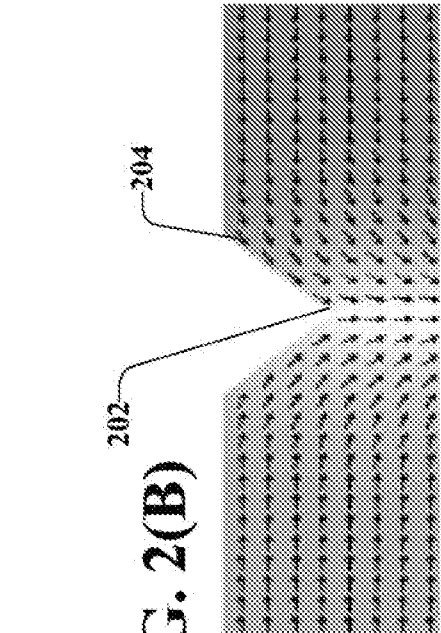


FIG. 2(A)

FIG. 2(B)

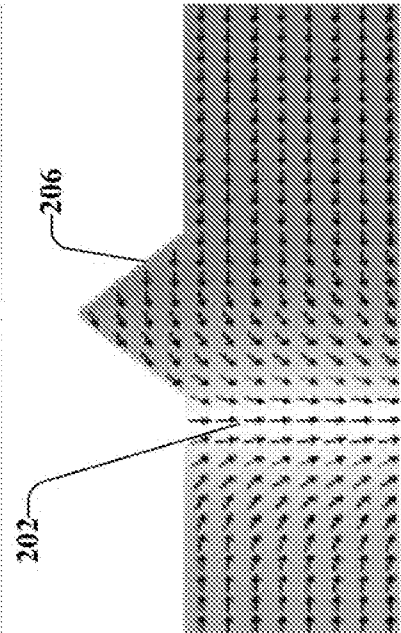
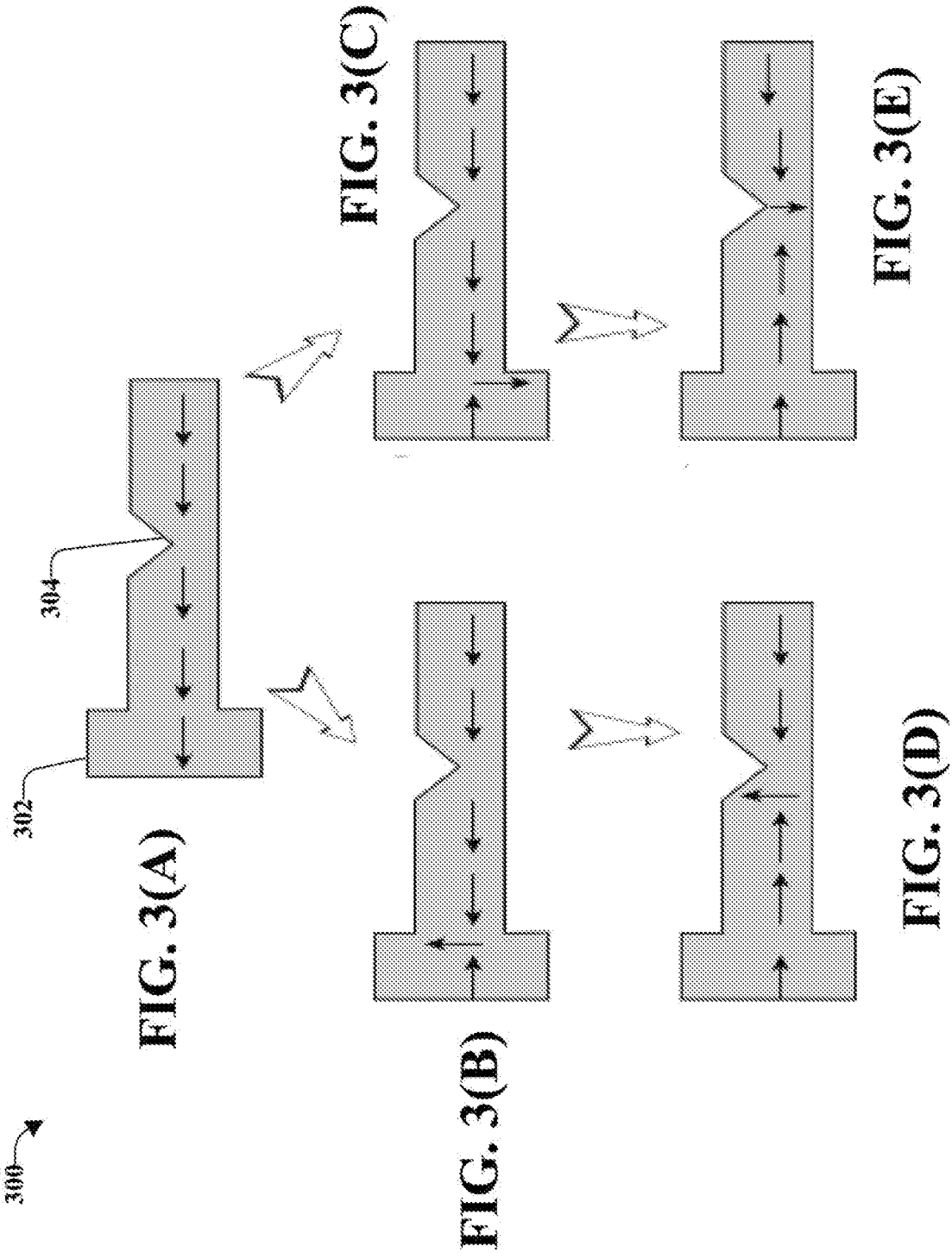
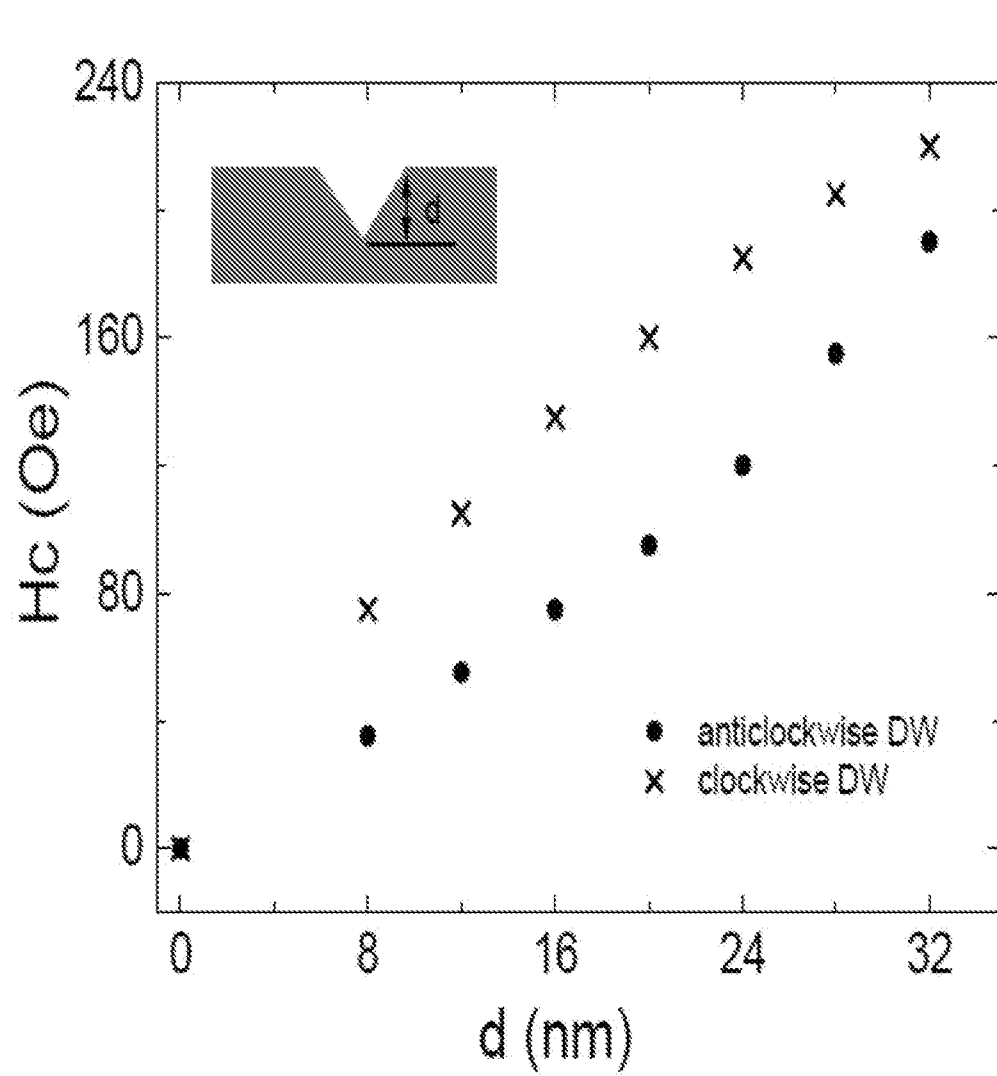


FIG. 2(C)

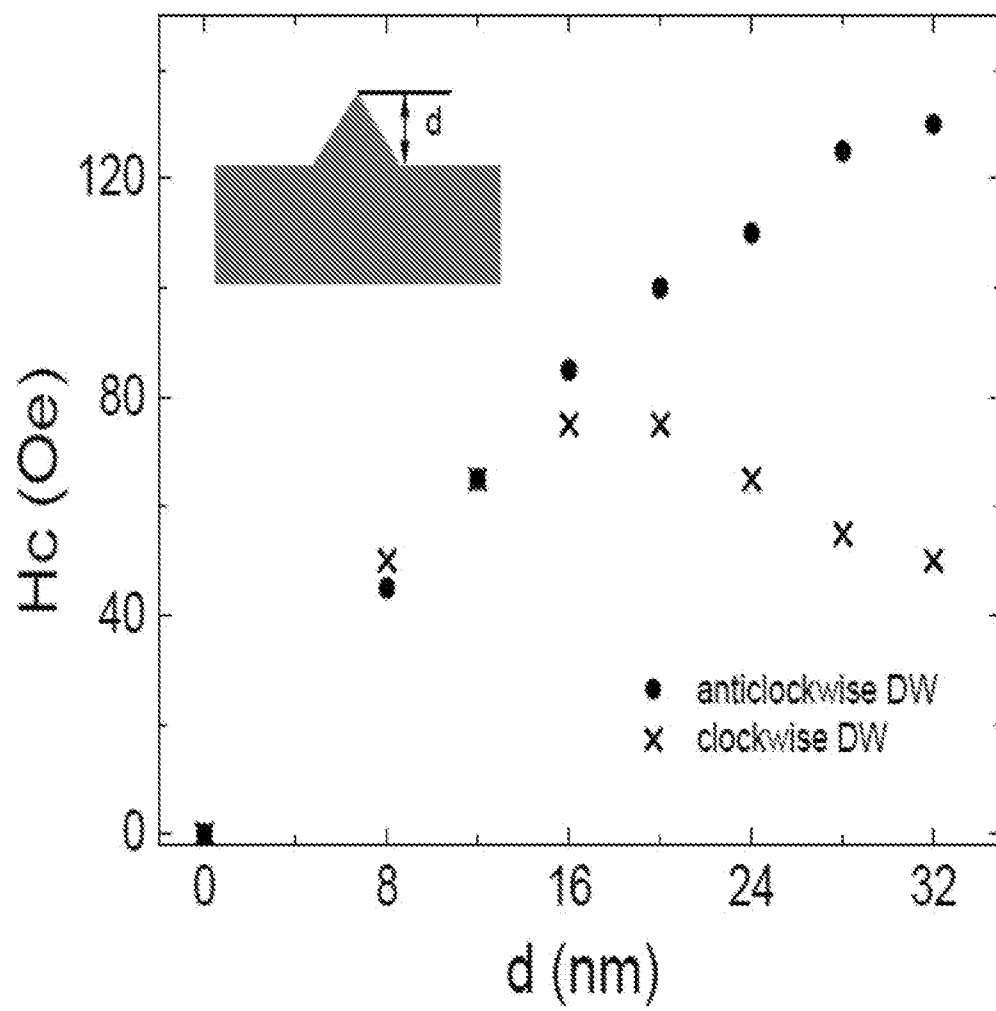
FIG. 2(D)

200



**FIG. 4**

500

**FIG. 5**

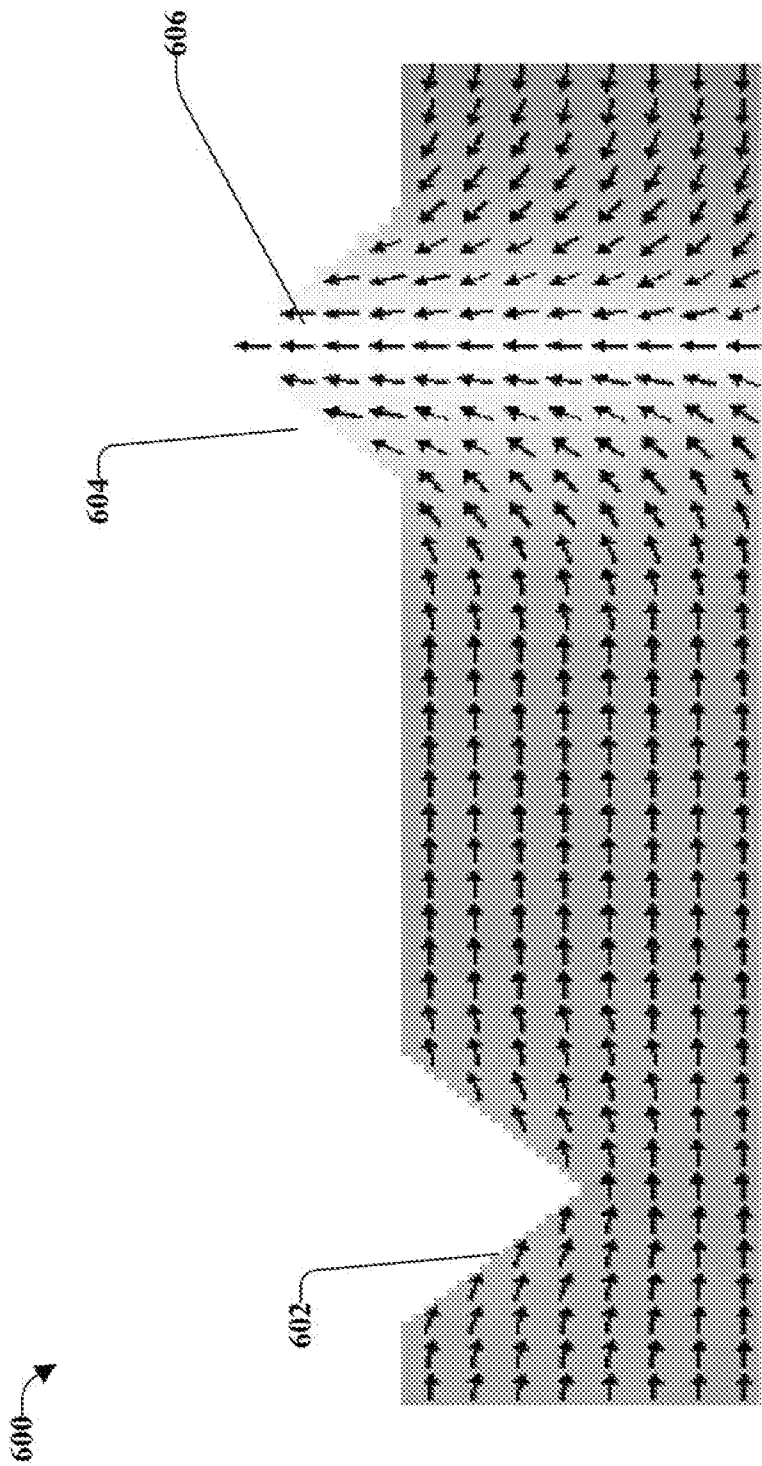


FIG. 6

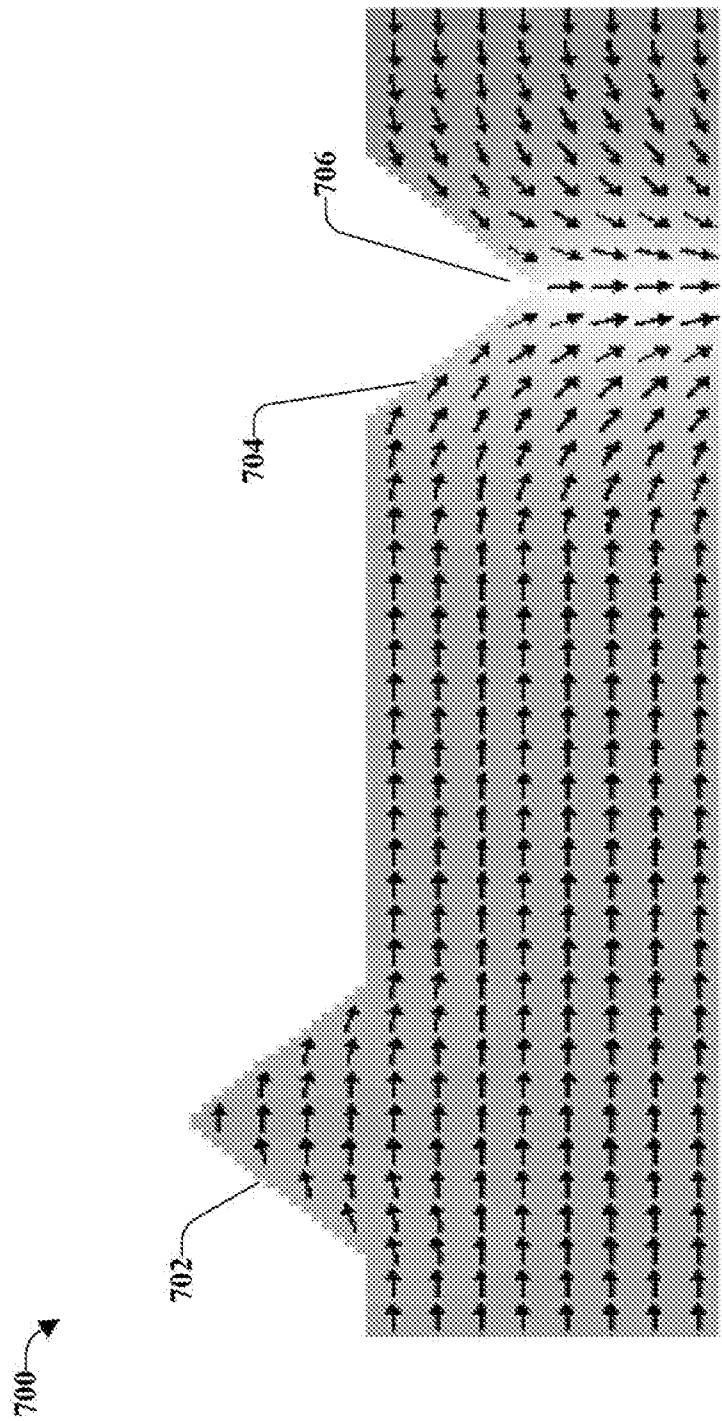
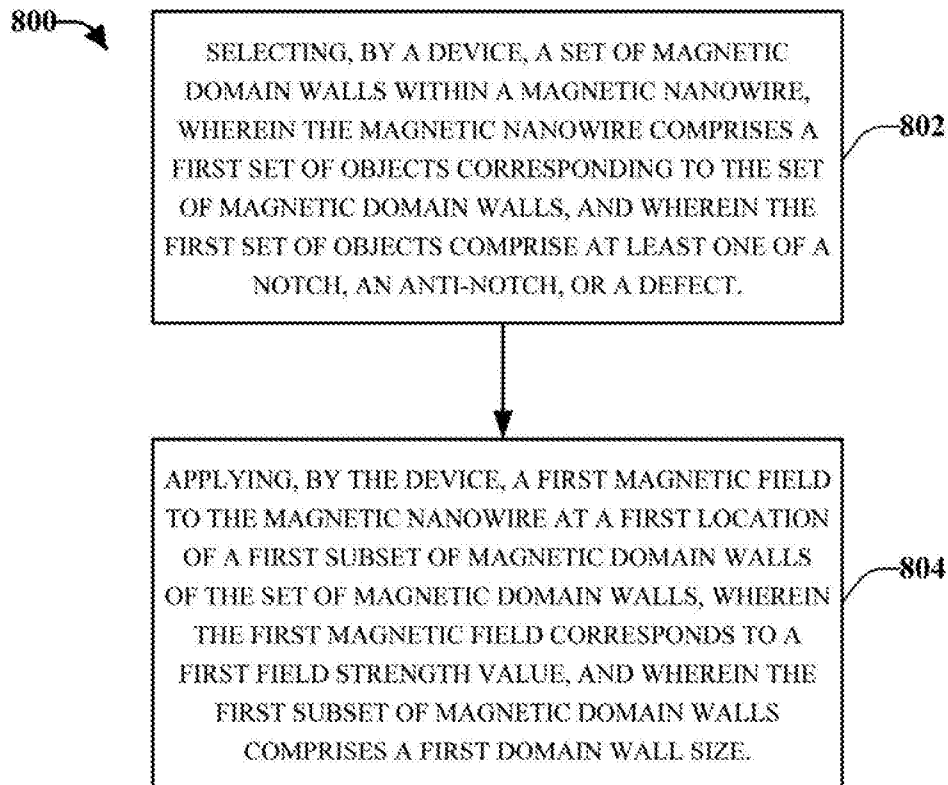
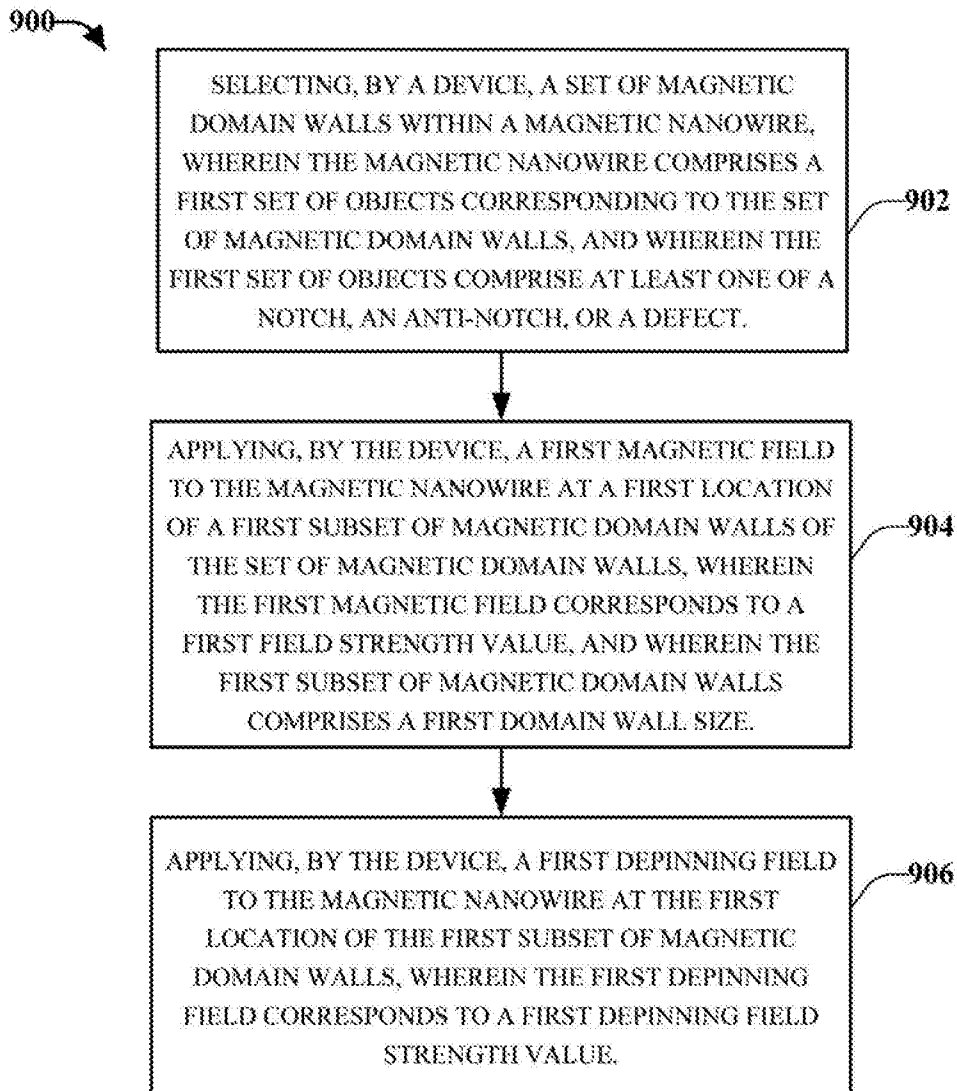
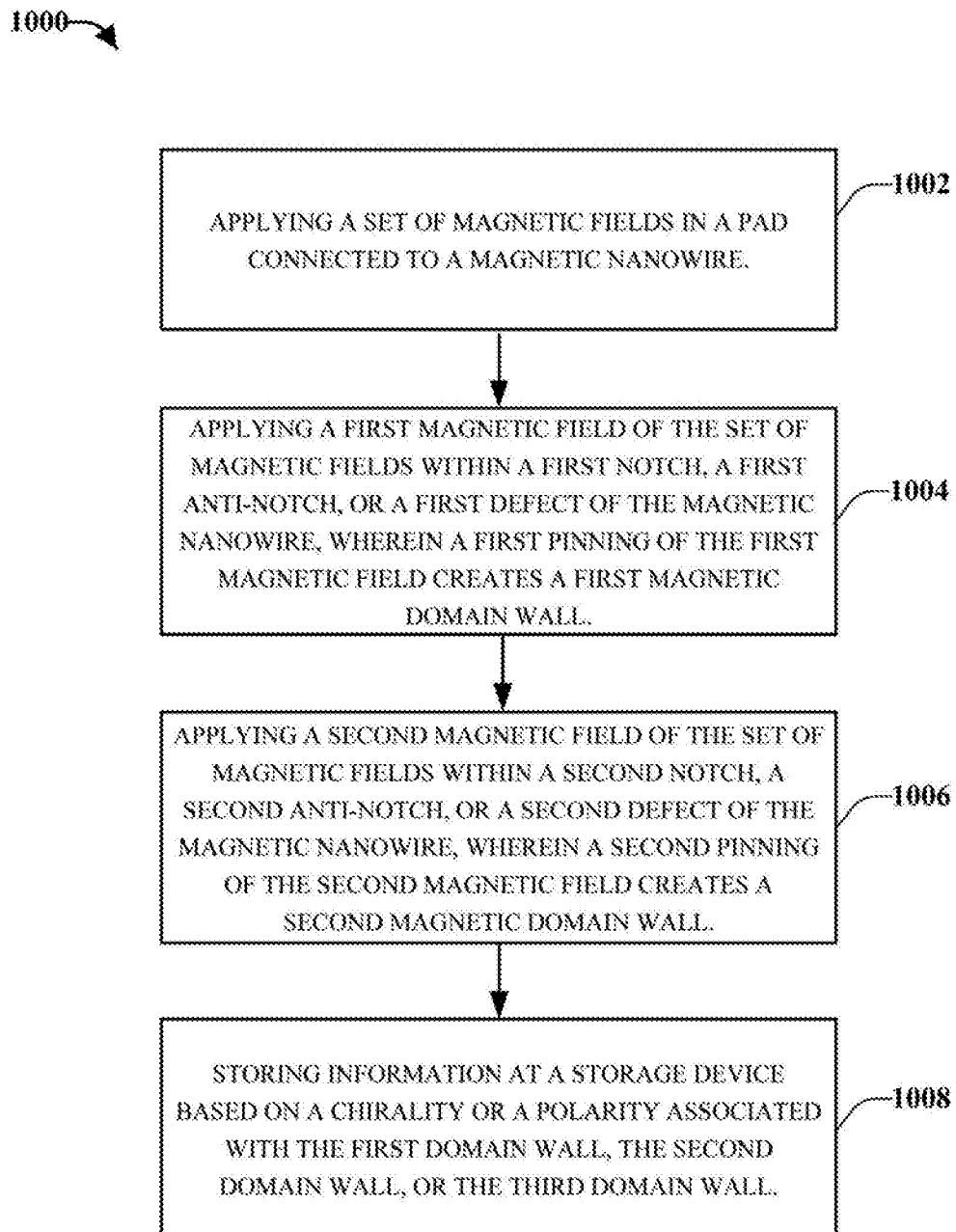


FIG. 7

**FIG. 8**

**FIG. 9**

**FIG. 10**

INTERNATIONAL SEARCH REPORT

International application No.

PCT/CN2015/075001

A. CLASSIFICATION OF SUBJECT MATTER

G11C 19/08(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)

G11C

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

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

CNPAT,WPI,EPODOC,CNKI magnetic, domain, wall?, pin+, depinning, trap, notch?, depression, defect, indentation, pad

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2007132174 A1 (INGENIA HOLDINGS UK LIMITED ET AL.) 22 November 2007 (2007-11-22) description, pages 6, 16-21, 28 and figures 1-4B	1-3,5-8,11-13,17
Y	WO 2007132174 A1 (INGENIA HOLDINGS UK LIMITED ET AL.) 22 November 2007 (2007-11-22) description, pages 6, 16-21, 28 and figures 1-4B	4,10,18-20
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A	US 2004252539 A1 (INTERNATIONAL BUSINESS MACHINES CORPORATION) 16 December 2004 (2004-12-16) the whole document	1-20



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

29 May 2015

Date of mailing of the international search report

29 June 2015

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/CN2015/075001

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/CN2015/075001

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