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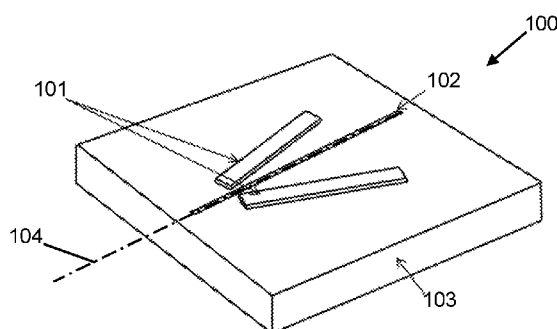
(54) **Title:** MAGNETIC STORAGE DEVICES AND METHODS

Fig. 1

(57) **Abstract:** The disclosure relates to information storage using magnetic domains or magnetic domain walls, and relates to methods of moving, creating, detecting and transforming the structure of magnetic domain walls using mechanical strain induced by electric fields. Applications include information storage and processing devices with high energy efficiency and small dimensions. Example embodiments include a magnetic storage device (100) comprising: an electroactive element (103) comprising a piezoelectric or electrostrictive element having first and second electrodes (101) arranged to apply an electric field across the electroactive element (103) to induce a strain; and a magnetic wire (102) having a plurality of magnetic domains separated by domain walls, the magnetic wire (102) aligned along an axis and mechanically coupled to the electroactive element (103); wherein the first and second electrodes (101) are arranged such that the electric field is aligned in a direction having a component orthogonal to the axis (104) of the magnetic wire (102), a magnitude of the electric field having a gradient along the axis (104) of the magnetic wire (102) to cause movement of the magnetic domains along the axis (104) of the magnetic wire (102).

MAGNETIC STORAGE DEVICES AND METHODS

Field of the Invention

The invention relates to information storage using magnetic domains and magnetic domain walls, and relates to methods of moving, creating, detecting and transforming the structure of magnetic domain walls using mechanical strain induced by electric fields. Applications include information storage and processing devices with high energy efficiency and small dimensions.

Background

The vast majority of present technologies for information storage (e.g. random access memory (RAM) such as flash memory, SRAM and DRAM) and logical processing (e.g. central processing units (CPUs)) rely on storing and moving electrical charge for their operation. Inherent limitations with the use of electrical charge are volatility, due to charge leakage, and energy dissipation due to the need to pass electrical currents through resistive components. These are now critical limitations hampering the drive towards further improvements in device performance. To address these limitations, modern concepts for information storage and processing are based on magnetism rather than electronics [references 1-5].

Magnetic Random Access Memory (MRAM) stores information in the magnetic state of a ferromagnetic element. Magnetic Racetrack memory stores information in the magnetic domain state of a ferromagnetic wire. Individual bits of information are separated by magnetic domain walls, or the domain wall itself can represent the bit of information. Information is moved between write and read positions by moving the magnetic domain walls along the ferromagnetic wire using spin transfer torque. It has been proposed that the racetrack memory concept is scalable to a three-dimensional storage architecture. Alternative designs for magnetic information storage utilising three dimensions have been proposed [references 6, 7]. One design consists of stacks of thin ferromagnetic layers separated by non-magnetic spacer layers. The magnetic coupling between adjacent ferromagnetic layers is tuned by the thickness of the spacer layer and can be ferromagnetic or antiferromagnetic. Information is stored in the form of a magnetic domain wall (also referred to as a soliton), represented by a sharp break or continuous rotation in the ordering of the magnetic layers along the stack. Another design consists of layers of magnetic wires in a stacked arrangement. Magnetic

domain walls are moved along each magnetic wire, representing a separate shift register type of memory device. The three dimensional designs offer significant increases in storage density compared to two dimensional designs. Proposals for carrying out logical processing operations involve moving magnetic domain walls
5 around circuits constructed from magnetic wires. Information can be represented by the presence or absence of a domain wall, by the direction of magnetisation in the region between domain walls, or by the chirality of the domain wall [reference 8].

These concepts address the problem of volatility, but still rely on electrical currents or
10 magnetic fields to write and move the magnetic information. Electrical currents create magnetic fields which act on the magnetic components, or transfer spin angular momentum (spin transfer torque) to the magnetic domains or domain walls. Because of the use of electrical currents, these devices also face limitations of energy dissipation, plus an additional restriction on storage density because stray magnetic
15 fields from current carrying wires can influence neighbouring components. These limitations prevent magnetic based concepts from competing effectively with traditional electronic based devices.

One solution to overcome these limitations is to use electric fields to control the
20 magnetic state of the device. A way to implement electric field control of magnetism is via voltage-induced strain-mediated control of the magnetisation in hybrid piezoelectric/ferromagnetic structures. This technique has been demonstrated as a viable way to control the magnetic anisotropy in ferromagnetic thin films [references 9-15] and to alter the domain state of magnetic nanoelements [reference 16]. However,
25 none of these approaches have succeeded in creating magnetic domain walls or in moving them between desired positions by design, with the exception of moving domain walls partially around ring structures [reference 81], but rather have only moved them between randomly occurring pinning sites or ferroelectric domains [references 17-21], or have pinned a domain wall which is moved by a magnetic field
30 [reference 22].

Domain walls also offer a unique type of highly localized and mobile magnetic field which can be used in Lab-on-Chip devices [references 23, 24]

Dean et al [reference 25] disclose artificial multiferroic systems combining piezoelectric and piezomagnetic materials, in which models show how localized strains in a piezoelectric film coupled to a piezomagnetic nanowire can attract and pin magnetic domain walls, synchronous switching of addressable contacts enabling controlled movement of pinning sites, and hence domain walls, in the nanowire without applied magnetic field or spin-polarized current, irrespective of domain wall structure. Lei et al [reference 22] discloses a lateral geometry allowing for memory and logic functions to be constructed using magnetic domain walls in nanowires, in which a domain wall propagation in a magnetic strip is controlled by a voltage applied across an underlying piezoelectric layer, an induced stress resulting in a local modification of the field or current required to propagate the domain wall. Sohn et al [Reference 81] disclose a device in which a ferromagnetic ring is fabricated on the surface of a PMN-PT (011) substrate. An electric field applied across the thickness direction of the substrate induces a uniaxial strain in the plane of the ferromagnetic ring which causes magnetic domain walls to move partially around the ring towards the minimum energy configuration.

Summary of the Invention

In accordance with a first aspect there is provided a magnetic storage device comprising:

an electroactive element comprising a piezoelectric or electrostrictive element having first and second electrodes arranged to apply an electric field across the electroactive element to induce a strain; and

a magnetic wire having a plurality of magnetic domains separated by magnetic domain walls, the magnetic wire aligned along an axis and mechanically coupled to the electroactive element;

wherein the first and second electrodes are arranged such that the electric field is aligned in a direction having a component orthogonal to the axis of the magnetic wire, a magnitude of the induced strain having a gradient along the axis of the magnetic wire to cause movement of the magnetic domain walls along the axis of the magnetic wire.

The electroactive element may be a substrate, i.e. a base on to which the magnetic wire and other components are deposited.

The component of the direction of the electric field orthogonal to the axis of the magnetic wire may be at least 50%, i.e. the direction being at least 45 degrees to the axis of the wire. In some embodiments the direction may be substantially orthogonal to the axis of the magnetic wire.

5

The first and second electrodes may be provided on opposing sides of the magnetic wire. A distance between the first and second electrodes may vary along the axis of the magnetic wire, thereby producing an electric field gradient along the axis that produces the induced strain gradient.

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The pair of electrodes may be provided within trenches in the electroactive element. The trenches may have a depth that varies in a direction along the axis of the magnetic wire, thereby producing the induced strain gradient as a result of a variation in clamping of the electroactive element along the axis.

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The first and second electrodes may be positioned across the thickness of the electroactive element where the electroactive element consists of a material or structure that produces an isotropic or an anisotropic strain response in the plane of the layer when an electric field is applied orthogonal to the plane of the layer e.g. PMN-PT [reference 77]. The width or thickness of the electroactive element may vary along the axis of the magnetic wire so that a gradient of the induced strain is created along the axis of the wire caused by variation in the clamping of the electroactive element by the surrounding material.

20

25 In some embodiments one of the electrodes may comprise the magnetic wire, i.e. the magnetic wire may provide at least a portion of one of the electrodes.

The magnetic storage device may comprise one or more further pairs of electrodes provided on opposing sides of the magnetic wire and separated from the first and second electrodes along the axis of the magnetic wire. Further such pairs of electrodes may be used to move magnetic domain walls further along the wire or to allow domain walls to be slowed down, stopped or reversed along the wire.

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The magnetic wire may be one of a plurality of magnetic wires aligned along the axis extending between the first and second electrodes, the plurality of magnetic wires

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being separated from each other by layers of a nonmagnetic material. A plurality of wires may allow increased numbers of magnetic domain walls to be moved using a common strain field. The plurality of magnetic wires may be encased with a nonmagnetic material, in order to provide an improved mechanical coupling with the electroactive element.

The magnetic wire or the plurality of magnetic wires may be embedded within the electroactive element, which results in improved coupling to the electroactive element.

The first and second electrodes may extend across opposing walls of the electroactive element on either side of the magnetic wire, a thickness of each wall tapering along the axis of the magnetic wire. Varying a thickness of a wall on either side of the magnetic wire allows the strain gradient to be better controlled and the strain to be of greater magnitude due to the reduced clamping effects.

The magnetic wire or the plurality of magnetic wires may consist of or comprise a ferromagnetic, ferrimagnetic or antiferromagnetic material.

The magnetic storage device may comprise a stack of alternating magnetic and nonmagnetic layers attached to the magnetic wire and the electrostrictive element between the first and second electrodes.

The or each magnetic wire in the magnetic storage device may be between 10 and 100nm in width and 1µm or more in length.

In accordance with a second aspect there is provided a method of operating a magnetic storage device, the device comprising:

an electroactive element comprising a piezoelectric or electrostrictive element having first and second electrodes for applying an electric field across the electroactive element to induce a strain; and

a magnetic wire having a plurality of magnetic domains separated by domain walls, the magnetic wire aligned along an axis and mechanically coupled to the electroactive element;

the method comprising applying a voltage signal between the first and second electrodes to generate an electric field across the electroactive element that generates an induced strain in the magnetic wire, the applied voltage signal having a temporal profile sufficient to cause the plurality of magnetic domain walls to move along the axis of the wire.

The voltage signal may be applied between the first and second electrodes as a pulse having a rise time or a fall time of less than 10 ns, optionally between 0.1 ns and 10 ns, optionally between 0.1 ns and 5 ns, optionally less than 0.1 ns. The rise time or fall time of the pulse being less than the timescale for damping of the precessional magnetisation dynamics allows the signal to cause movement of the magnetic domain walls. In practice, a faster rise or fall will tend to be more effective.

The first and second electrodes may be arranged such that the electric field is aligned in a direction having a component orthogonal to the axis of the magnetic wire. In some embodiments the component of the direction of the electric field that is orthogonal to the axis of the magnetic wire may be at least 50%, i.e. the direction being at least 45 degrees to the axis of the wire. In some embodiments the direction may be substantially orthogonal to the axis of the magnetic wire.

A magnitude of the induced strain may have a gradient along the axis of the magnetic wire. The strain gradient may for example be greater than 1×10^{-3} per micrometre along at least a portion of the magnetic wire.

The plurality of magnetic domains may move at least 10nm, 100nm, 1µm or more along the axis of the wire in response to the induced strain.

As with the first aspect, one of the electrodes may comprise the magnetic wire, i.e. the magnetic wire may provide at least a portion of one of the electrodes.

Other features relating to the first aspect may also be applied to the second aspect.

In accordance with a third aspect there is provided a magnetic storage device comprising:

an electroactive element comprising a piezoelectric or electrostrictive element having first and second electrodes for applying an electric field across the electroactive element to induce a strain; and

5 a stack of alternating magnetic and nonmagnetic layers, the stack having a base layer mechanically coupled to the electroactive element;

wherein the first and second electrodes are arranged such that the induced strain is aligned in a direction parallel to the plane of the layers of the stack to provide a strain gradient between the base layer and an opposing top layer of the stack to cause movement of a domain wall between layers of the stack.

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The pair of electrodes may be provided within trenches in the electroactive element on opposing sides of the stack.

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The first and second electrodes may be positioned across the thickness of the electroactive element where the electroactive element consists of a material or structure that produces an isotropic or an anisotropic strain response in the plane of the layer when an electric field is applied orthogonal to the plane of the layer

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The base layer of the stack may form one electrode comprising part of the pair of electrodes.

The top layer of the stack may consist of a material having a higher Young's modulus than the bottom layer.

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The magnetic storage device may comprise a magnetic wire extending along an axis between the electrodes. The magnetic wire may be disposed, i.e. located, between the base layer of the stack and the electroactive element.

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The stack may be embedded within the electroactive element, thereby allowing a greater coupling to the electroactive element.

Each of the magnetic layers may consist of or comprise a ferromagnetic, ferrimagnetic or antiferromagnetic material.

The magnetic configuration of each of the magnetic layers may comprise a single magnetic domain or multiple magnetic domains.

In accordance with a fourth aspect there is provided a magnetic storage device
5 comprising:

an electroactive element comprising a piezoelectric or electrostrictive element having first and second electrodes arranged to apply an electric field across the electroactive element to induce a strain; and

a magnetic wire having first and second magnetic domains separated by a
10 vortex domain wall, the magnetic wire mechanically coupled to the electroactive element;

wherein the first and second electrodes are arranged such that the induced strain in the electroactive element causes a chirality of the vortex domain wall to change.

15

The magnetic wire may be aligned along an axis extending between the first and second electrodes.

The magnetic wire may be curved, for example in the form of a portion of a circular or
20 elliptical curve.

The first and second electrodes may be positioned across the thickness of the electroactive element where the electroactive element consists of a material or structure that produces an isotropic or an anisotropic strain response in the plane of
25 the layer when an electric field is applied orthogonal to the plane of the layer

The magnetic wire may form one electrode comprising part of the pair of electrodes.

The magnetic storage device may comprise a magnetic tunnel junction structure
30 coupled to the magnetic wire.

In accordance with a fifth aspect there is provided a method of operating a magnetic storage device according to the fourth aspect, the method comprising:

applying a voltage signal between the first and second electrodes sufficient to generate a strain in the electroactive element that causes the domain wall in the magnetic wire to switch chirality; and

measuring the chirality of the vortex domain wall by measuring a resistance of
5 the magnetic tunnel junction coupled to the magnetic wire.

The voltage signal may be applied between the first and second electrodes as a pulse having a rise time and/or a fall time of less than 10 ns, optionally between 0.1 ns and 10 ns, optionally between 0.1 ns and 5 ns, optionally less than 0.1ns The rise time or
10 fall time of the pulse being less than the timescale for damping of the precessional magnetisation dynamics allows the signal to cause switching of the chirality of the magnetic domain walls.

Detailed Description

15 The invention is described in further detail below by way of example and with reference to the accompanying drawings, in which:

figure 1 is a schematic drawing of an example device having a magnetic wire on the surface of a piezoelectric substrate between a pair of slanted electrodes;

figure 2 is a schematic drawing of an example device having a magnetic wire
20 on the surface of a piezoelectric substrate with etched trenches for electrode contacts on opposing sides of the wire;

figure 3 is a schematic drawing of an example device having a magnetic wire on the surface of a piezoelectric substrate with etched trenches having a non-uniform depth in the substrate on opposing sides of the wire;

25 figure 4 is a schematic drawing of an example device similar to that of figure 3, in which a stack of magnetic wires is provided between the first and second electrodes;

figure 5 is a schematic drawing of an example device in which a stack of wires is embedded within a piezoelectric element having tapered walls on opposing sides of
30 the stack of wires;

figure 6a is a schematic drawing of an example device in which a varying strain profile is applied across the wire;

figure 6b is a plot of strain as a function of distance along the wire of figure 6a;

figure 7 is a schematic diagram of a shift register with a domain wall injector and a readout circuit at opposing ends of a magnetic wire;

figures 8i) to 8iv) are schematic diagrams illustrating a series of operational states for an example domain wall injector based on a magnetic wire;

5 figure 9 is a schematic diagram of a logical OR circuit based on a magnetic wire;

figure 10 is a schematic drawing of an example device having a stack of magnetic and nonmagnetic layers on a piezoelectric substrate with electrodes on opposing sides of the stack;

10 figures 11a and 11b are side and plan view schematic drawings of an example device having a stack of magnetic and nonmagnetic layers on a piezoelectric substrate with an additional magnetic wire and electrodes arranged to provide an electric field gradient for movement of domains along the axis of the wire;

figure 12 is a schematic drawing of an alternative example device to that of
15 figure 10, in which the stack is embedded within the piezoelectric substrate;

figure 13a is a schematic drawing of an example device having a magnetic wire on a piezoelectric substrate having electrodes on opposing sides of the wire;

figure 13b is a side sectional view of the device of figure 13a;

figure 14a is a schematic drawing of an example device having a magnetic wire
20 on a piezoelectric substrate having electrodes on opposing sides of the wire, in which the electrodes are disposed on trenches on opposing sides of the wire;

figure 14b is a side sectional view of the device of figure 14a;

figure 15a is a schematic drawing of an example device having a magnetic wire on a substrate overlaid with a dielectric layer and an electrode;

25 figure 15b is a side sectional view of the device of figure 15a;

figure 16 is a schematic drawing of a magnetic domain wall in a curved section of a magnetic wire;

figure 17 is a schematic drawing of a magnetic domain wall confined to a straight section of a magnetic wire on a piezoelectric substrate;

30 figure 18 is a schematic drawing of an example information storage device with a chiral domain wall positioned along a curved section of a stack of magnetic wires;

figure 19a is a schematic drawing of an example device consisting of a nickel ring on a PMT-PT substrate;

figure 19b is a schematic plot of uniaxial strain as a function of electric field applied to the PMN-PT substrate of the device of figure 19a;

figure 19c is a schematic representation of a vortex domain wall in a magnetic nanowire;

5 figure 20 is a series of XMCD-PEEM images of strain-induced chirality switching in vortex domain walls;

figure 21 is a series of micromagnetic simulations of a head to head vortex domain wall under the action of a uniaxial magnetic anisotropy energy;

10 figures 22 and 23 show the results of further micromagnetic simulations using strain applied on long timescales compared to the magnetisation dynamics;

figure 24 is a schematic drawing of an example information storage device comprising a magnetic tunnel junction structure with ferromagnetic top and bottom electrodes fabricated on a piezoelectric substrate;

15 figure 25 is a series of a schematic diagrams of an example device having a magnetic wire on a piezoelectric substrate, with a voltage applied to electrodes on opposing sides of the wire inducing a mechanical strain and uniaxial anisotropy favouring an easy axis transverse to the wire;

figure 26 is a further example device having electrodes positioned across the thickness direction of an electroactive layer; and

20 figure 27 is an illustration of the results of micromechanical calculations performed on the device of figure 26.

As disclosed herein, spatial and/or temporal mechanic strain profiles can be used to create spatial and/or temporal magnetic anisotropy energy profiles in magnetic devices
25 fabricated from magnetostrictive materials. Domain walls in the magnetic devices can be moved and/or transformed by the spatial and/or temporal magnetic energy profiles.

Devices described herein can be broadly defined in three categories:

- 30 1. Devices in which a gradient of magnetic anisotropy energy is created and used to move magnetic domain walls
2. Devices in which a temporal change in the magnetic anisotropy energy profile is induced in the region of a magnetic domain wall. The change in magnetic anisotropy energy profile induces motion of the magnetic domain wall.
- 35 3. Devices in which an inhomogeneous magnetic anisotropy energy profile induces a change in the structure of a magnetic domain wall.

Magnetic Anisotropy Gradients

Magnetic anisotropy energy describes how the energy of a magnetic system depends upon the direction or axis of the magnetisation. The direction or axis that produces the minimum in this energy is referred to as the “easy axis” and the system will prefer to have the magnetisation pointing along this direction or axis. Magnetic anisotropy energy can arise from several competing origins including: magnetocrystalline anisotropy (the energy depends upon the angle between the magnetisation and the crystal lattice), shape anisotropy (the geometrical shape of the magnetic structure influences the energy because the internal magnetic fields depend upon the number of magnetic poles at the free surfaces of the structure and their separation) and magnetostriction (distortion of the sample dimensions, and hence the crystal lattice, by the application of mechanical strain affects the crystal symmetry and so alters the magnetocrystalline anisotropy energy). In the case of a long, thin magnetic nanowire, with negligible magnetocrystalline anisotropy, the large aspect ratio will favour the magnetisation pointing in the direction parallel to the axis of the wire. In the case of a ferromagnet, adjacent regions of the wire with the magnetisation pointing parallel to the axis of the wire, but 180° to each other are known as magnetic domains, and they possess the same magnetic anisotropy energy. The boundary between these domains consists of a region in which the magnetisation rotates away from the axis of the wire. The magnetic anisotropy energy in the region of this “domain wall” is larger because the magnetisation is rotated away from the easy axis. There is also an energy cost (exchange energy) which arises from the non-zero angle between adjacent atomic magnetic moments within the domain wall. These competing energy terms result in domain walls having dimensions of the order 10-100nm. Domains and domain walls also exist in antiferromagnets and ferrimagnets, where domain walls separate regions in which the axes of the alternating spin sublattices change, or the order of the alternating sublattices changes. The axes of the magnetisation can rotate away from the easy axes within the domain wall, which will cost energy locally.

Magnetic domain walls can be considered as stable, macroscopic objects which possess inertia [references 48, 49] and can be moved along a nanowire under the influence of a driving force. Several of the concepts for magnetic information storage or processing require the ability to move magnetic domain walls along nanowires. Fundamentally, this requires the creation of a gradient in the energy of the system (this is an equivalent way to describe a driving force), to which the domain wall

responds by moving to a location on the nanowire that minimises the energy. Typically, the energy gradient is produced by the application of a magnetic field or by transferring angular momentum to the domain wall via an electrical current passed through the nanowire (a process known as spin transfer torque (STT)). It is also possible to move a magnetic domain wall by creating a gradient in the magnetic anisotropy energy. This can be achieved by producing gradients in the width of the wire or in the composition, by ion implantation of non-magnetic atoms. These methods result in fixed magnetic anisotropy gradients which produce favoured directions of motion for the magnetic domain wall, but the domain wall must still be driven by another external influence, such as a magnetic field or electrical current. However, if the gradient in the magnetic anisotropy energy could be switched on and off, then it could be used to move domain walls between desired positions on demand. The concepts described herein relate to creating gradients in the magnetic anisotropy energy of a nanowire that can be switched on and off and tuned by the application of voltage-induced strain gradients to specific sections of the nanowire. The strain gradient is converted to an anisotropy gradient by the inverse magnetostriction effect. This will enable the motion of the domain walls to be induced and controlled by the applied voltage which will set both the magnitude and direction of the anisotropy gradient.

20

Depending upon the magnetic material and the nanowire dimensions, various types of domain wall are possible, including 360° transverse and vortex walls. In the case where the magnetisation points perpendicular to the plane of the magnetic film, a domain wall can be of the Bloch or Néel type corresponding to the magnetisation in the wall rotating in the plane perpendicular to or along the direction of the wire respectively. For most of the detailed explanations described herein we will use the example of a 180° transverse domain wall because it is the simplest structure to investigate, but we note that the same techniques will be effective for controlling the other types of domain walls.

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Gradients of magnetic anisotropy energy may be created and controlled within magnetic wires, stacks of wires or stacks of alternating magnetic and nonmagnetic layers. Magnetic domain walls can be created, moved and detected within the wires, stacks of wires or stacks of layers using voltage induced strains. In some cases, the

gradient in the anisotropy energy may be zero, representing a finite uniform anisotropy energy.

5 A common feature to several examples described herein is that of arranging voltage contacts on a piezoelectric or electrostrictive element (typically a substrate, although the piezoelectric or electrostrictive element may alternatively be provided in a different form) in a hybrid structure. The voltage contacts are arranged such that the application of a voltage to the contacts induces a mechanical strain in the substrate which is transmitted to the magnetic part of the device, in which it creates a
10 mechanical strain in a region of the magnetic wire, stack of wires or stack of layers. When the magnetic material is magnetostrictive, the strain produces an additional magnetic anisotropy energy along a section of the wire, stack of wires or stack of layers. Depending on the geometry of the contacts, the induced magnetic anisotropy energy can have a nonzero gradient in part of the wire, stack of wires or stack of
15 layers. In some cases the anisotropy energy can be constant along the whole or part section of the wire, stack of wires or stack of layers.

The magnetic wires and layers described herein can be fabricated from ferromagnetic, ferrimagnetic or antiferromagnetic materials. The magnetisation can be oriented in the
20 plane of the layers or wires, along the direction of the wires, or perpendicular to the direction of the wire or wires. Alternatively, the magnetisation can be oriented perpendicular to the plane of the layers or wires. Magnetic domain walls can be any type of domain wall supported by the magnetisation of the wire, including but not limited to transverse 90° , 180° , 360° , vortex, Bloch and Néel walls. Stacks of
25 magnetic layers can consist of magnetic layers with the magnetic easy axis lying in the plane of the layers or perpendicular to the plane of the layers. Domain walls in the magnetic stacks can be sharp kink solitons, broad chiral solitons or any kind of soliton, as for example described by Cowburn [reference 6].

30 Inducing a gradient in the magnetic anisotropy energy in a region of a wire, stack of wires or stack of layers favouring/opposing the orientation of magnetization of one of the domains or of the magnetization inside the domain wall itself results in motion of the domain wall that will reduce the energy of the entire system. Inducing a constant contribution to the magnetic anisotropy energy in a region of a wire or a stack
35 favouring orientation of the magnetisation of one of the present domains, in

preference to adjacent domains, results in enlargement of that domain, hence motion of the domain walls at its edges.

5 The magnetic wire or stack can have a voltage contact, or it can be at a floating potential. It can be in direct electrical contact with the substrate or it can be separated by a thin electrically insulating layer.

10 A concept proposed by Dean [reference 25] moves magnetic domain walls along a ferromagnetic wire by creating a minimum in the magnetic anisotropy energy between pairs of voltage contacts positioned over a piezoelectric layer deposited on top of the wire. The domain wall is trapped in the energy minimum. The energy minimum is moved along the wire by changing the voltages on successive voltage contacts along the wire. The domain wall then moves along the wire with the energy minimum. The devices and methods described herein differ from those described by Dean in several ways. Firstly, the designs described here can produce a constant magnetic anisotropy energy gradient over several micrometres, allowing for much more rapid and energy efficient domain wall motion. This can allow multiple domain walls to be moved with a single voltage pulse applied to a single pair of voltage contacts, as opposed to only moving one domain wall at a time. The present designs can therefore be made to operate more efficiently. Secondly, the designs presented here can propel domain walls beyond the region of the voltage contacts. Domain walls will continue to move under their own inertia until viscous forces slow them down, or until they are stopped intentionally at the next set of voltage contacts. In the case of Dean's design, however, the domain walls are stopped by the energy minimum between successive voltage contacts and are not propelled beyond the region of the voltage contacts. The designs presented here do not necessarily produce minima in the magnetic anisotropy energy, although in some arrangements can produce an isolated maximum (or minimum) of magnetic anisotropy energy to allow for deceleration of a moving domain wall. The designs presented here also allow the magnetic part of the structure to be fabricated on top of an electroactive substrate, thereby allowing single crystal substrates to be used to maximise the piezoelectric effect. With Dean's design there will tend to be a degradation of performance because the piezoelectric material must be fabricated on top of the structure and so may not have such good structural and piezoelectric properties as single crystal substrates or in devices where the electroactive element can be deposited prior to deposition of a magnetic wire or layer.

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The designs presented here may, in some cases, allow the magnetic part of the structure and the voltage contacts to be fabricated in the same plane on top of the piezoelectric or electrostrictive substrate, thereby making fabrication simpler and cheaper.

The geometry of the contact arrangements presented here may also allow the addition of further contacts along the wire, or around the stack, for the purposes of read/write operations, without disrupting the function of the contacts for moving the domain walls.

Figures 1 to 5 illustrate example device structures according to the first of the above categories, i.e. devices in which a gradient of magnetic anisotropy energy is created and used to move magnetic domain walls. In each case, the gradient is created by applying a strain gradient to a magnetic wire using a piezoelectric or electrostrictive (hereinafter termed electroactive) element.

Moving Domain Walls Along a Magnetic Wire

Micromagnetic calculations show that transverse magnetic domain walls will move along nanowires under the influence of magnetic anisotropy energy gradients. These calculations reveal that domain walls can move with appreciable velocities for experimentally achievable anisotropy gradients. As an example, calculations have been made based on a transverse domain wall in a 100nm wide $\text{Fe}_{81}\text{Ga}_{19}$ nanowire. Based on snapshots taken at 0ns and 5ns, an average velocity of 45ms^{-1} resulted for a gradient of $10\text{kJm}^{-3}/\mu\text{m}$ and 140ms^{-1} for a gradient of $20\text{kJm}^{-3}/\mu\text{m}$. The dynamics of magnetic domain walls moving under the driving influence of a magnetic field or STT fall into three regimes: creep, viscous flow and Walker breakdown regimes. For very low driving forces, the domain wall motion is dominated by pinning sites created by defects within the material or device structure. Motion proceeds by the thermally activated transitions of domain walls between pinning sites and is a stochastic process. At larger driving forces the motion becomes more uniform and the domain wall proceeds at a constant velocity, which is proportional to the driving field or current and is determined by the damping properties of the magnetic material. At a critical driving force the domain wall motion becomes turbulent. This is known as the Walker limit and is characterised by a decrease in the domain wall velocity caused by

transformations of the domain wall structure. In the case of a transverse domain wall in a narrow nanowire with in-plane magnetisation the wall transforms to an anti-vortex structure and the vortex core oscillates back and forth across the width of the wire [reference 43]. Larger driving forces still increase the domain wall velocity, but the gyrating motion of the domain wall results in a smaller mobility (velocity per unit applied field or current) than observed below the Walker limit. Similar regimes are observed in wider nanowires where a vortex domain wall is the stable static structure, and in materials with perpendicular anisotropy where the turbulent flow is caused by oscillations between Bloch and Néel domain wall structures.

The ground state structure of a domain wall is known to depend upon the width of the nanowire and can be tuned by imposing an additional anisotropy using techniques such as voltage-induced strain. In the case of a material with perpendicular anisotropy this has been shown to tune the motion in the viscous flow and Walker breakdown regimes for domain walls moving under the action of STT [reference 61]. In the case of in-plane transverse domain walls it has been shown that the Walker limit can be delayed by the application of a magnetic field transverse to the wire or by the design of geometrical structures to inhibit the gyrating motion of the antivortex core.

Based upon these findings, it is clear that the structure and motion of magnetic domain walls in the shift gate devices will be influenced by both the gradient and the absolute value of the anisotropy energy. While the gradient in anisotropy energy is responsible for moving the domain wall along the wire, the absolute value of the anisotropy energy will determine the stability of the domain wall structure and therefore the velocity at which the Walker limit occurs.

Example Shift Gates

Voltage contacts can be arranged on the electroactive substrate. The direction of ferroelectric polarisation in the case of a piezoelectric substrate can be set such that when a voltage is applied between the contacts, or between the contacts and the magnetic wire, it produces a gradient in the strain tensors along the wire.

One example of an arrangement of gates to achieve this is shown in the device illustrated in figure 1. The contacts or electrodes 101 are fabricated in the same plane as a magnetic wire 102 on the surface of a piezoelectric substrate 103. The direction

of ferroelectric polarisation within the piezoelectric material is in the plane of the substrate 103 and orthogonal to the axis 104 of the magnetic wire 102, which serves to maximise the strain in that direction. The slanted angle of the contacts 101 with respect to the axis 104 of the magnetic wire 102 leads to a gradient in the electric field aligned in a direction orthogonal to the axis 104 of the wire 102 in the region of the wire 102 when a voltage is applied between the contacts 101, the electric field ranging from a maximum where the electrodes 101 are closest to a minimum where the electrodes are furthest apart. The piezoelectric response of the substrate 103 to the electric potential creates a corresponding gradient in mechanical strain along the axis 104 of the wire 102 in a direction orthogonal to the axis 104. When the wire 102 is made from a magnetostrictive material this induces a gradient in the magnetic anisotropy energy density along the axis of the wire. A magnetic domain wall in the region between the contacts will thereby be induced to move along the wire by this gradient in anisotropy energy density, in a direction that will tend to minimise the energy of the system.

A modification of the design of figure 1 is to etch the substrate such that the contacts can be embedded rather than provided on the surface. This alternative arrangement is depicted in the device 200 shown in figure 2, in which etched trenches 201 are provided in the substrate 103. The etching has the effect of reducing clamping of the mesa 202 to the surrounding substrate, thereby enhancing the magnitude of the strain and strain gradient induced in the magnetic wire 102. Another possible modification is to position the electrodes on the side walls 203 of the mesa 202 in the piezoelectric substrate 103 to increase the depth to which the electric field penetrates the mesa 202 and so to increase the strain response of the mesa 202, thereby enhancing the magnitude of the strain and strain gradient induced in the magnetic wire 102.

Another possible modification is to etch the substrate 103 such that the electrodes can be embedded into the substrate 103 and/or along the side walls 203 of the mesa 202 with trenches 301 having a non-uniform etch depth along the wire 102. This alternative is depicted in the device 300 shown in figure 3. The variation of the etch depth causes a variation in the depth to which the electric field penetrates into the piezoelectric substrate 103. The variation in the etch depth also causes variation in the extent to which the strain in the mesa 302 can relax. Both factors contribute to an enhancement of the gradient in the strain along the magnetic wire 102. The above-

mentioned designs and modifications can be applied on their own or in combination to produce the desired magnitude and profile of strain gradient.

5 A voltage pulse applied to a single pair of contacts, fabricated according to the arrangements mentioned above, will tend to propel a domain wall or a sequence of domain walls along the wire. When the voltage pulse is removed, or when the domain wall or walls leave the region of the gradient in the anisotropy energy density, the domain wall or walls will continue to move under their own inertia until stopped by viscous forces.

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A second arrangement of voltage contacts can be fabricated further along the wire 102 to move the domain wall or walls further along by the application of a voltage pulse to the second arrangement of contacts. By changing the polarity of this voltage pulse, or by fabricating the second arrangement of contacts with the angle to the wire, or the etch profile, in the opposite sense to the first arrangement of voltage contacts, it will 15 be possible to slow down or stop the moving domain wall or walls, and optionally to cause them to move back in the opposite direction.

Alternatively, a second arrangement of voltage contacts can be fabricated further 20 along the wire to move the domain wall or walls further along by the application of a voltage pulse to the second arrangement of contacts, but with the opposite polarity to the voltage pulse applied to the first arrangement of voltage contacts. This will move the domain wall or walls in the same direction along the wire if the angle to the wire, or the etch profile, for the second arrangement of voltage contacts is in the opposite 25 sense to the first arrangement of voltage contacts.

An extension of this design is to fabricate a sequence of independent contact arrangements along the wire with a possible partial overlap of neighbouring contact pairs/arrangements. Upon sequential application of a voltage to each pair of contacts a 30 domain wall, or a plurality of domain walls can move continuously or step-wise along the wire. This design is analogous to a domain wall ratchet demonstrated, for example by Franken et al. [reference 26]. However, the magnetic anisotropy energy profile is fully controllable during the domain wall motion so no external magnetic field is required to shift the domain walls.

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The methods described above can be applied to move domain walls in a shift register based upon the racetrack concept, where the mechanical strain replaces or reduces the requirement to use electrical current to move domain walls along the magnetic wire. The methods are also applicable in the domain wall based MRAM architecture proposed by NEC Corporation, Japan [reference 33].

The methods described above can be applied to designs for devices to carry out logical processing operations by moving domain walls around circuits constructed from magnetic wires. There, the methods will replace or reduce the requirements to use electrical currents or rotating magnetic fields to move the domain walls.

Moving Domain Walls Along a Stack of Magnetic Wires

The methods described in the preceding section can also be applied to an arrangement consisting of a plurality of magnetic wires in a stacked configuration with non-magnetic spacers between the wires. The stacking direction can be perpendicular to the plane of the piezoelectric substrate. Several stacks can be accommodated next to each other and between the same pairs of contacts. Each wire can contain one domain wall or a plurality of domain walls.

The stack of magnetic wires can be fabricated on top of the piezoelectric substrate, in the position of the single wire 102 depicted in figures 1 to 3. A possible arrangement is depicted in the device 400 shown in figure 4. As with the device 300 in figure 3, etched trenches 301 are provided in the substrate 103 to provide a gradient in the strain applied across the wire. Instead of one wire, however, a plurality of wires 402 is provided, separated from each other by layers of a nonmagnetic material. A single voltage pulse applied to the electrodes will move a domain wall or sequence of domain walls along each wire in the stack 402. Domain walls can be injected in to each wire within the stack 402 independently, thereby allowing each wire to function as an independent shift register.

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A modification to the design shown in figure 4 would be to encase the stack 402 of magnetic wires with a non-magnetic material to enhance the transmission of strain to the wires lying higher up in the stack.

Another modification would be to embed a single wire or stack of wires within the piezoelectric substrate 103. Voltages applied to contacts in any of the arrangements described already in this document would produce a gradient in the strain along the length of the wires

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Another modification, an example of which is illustrated by the device 500 shown in figure 5, would be to embed a single wire or the stack of wires within a mesa 503 formed in the piezoelectric substrate 103, with voltage contacts 501a-d along the side of the mesa 502. An angled arrangement of the contacts 501a-d with respect to the axes of the wires 502, or a non-uniform etch depth of the mesa 503, would produce the gradient in the strain along the length of the wires 502. Figure 5 shows first and second electrodes 501a, 501b on opposing sides of the wires 502 at a first position along the wires 502, with third and fourth electrodes 501c, 501d on opposing sides of the wires 502 at a position separated from the first and second electrodes 501a, 501b along the axis of the wires 502. This arrangement allows for movement of domain walls along the wires in either direction, as the gradient applied to the wires 502 by the first and second electrodes 501a, 501b is opposite to that applied by the third and fourth electrodes 501c, 501d. In alternative arrangements the gradients may be configured to be in the same sense, to allow domains to be further propelled along the wires 502.

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An example circuit element 600 to move magnetic domain walls along a nanowire is depicted schematically in figure 6a. Hereafter this circuit element may alternatively be referred to as a “shift gate”. The shift gate 600 comprises a magnetic nanowire 601 fabricated on top of an electroactive (piezoelectric or electrostrictive) element 603, in this example forming a substrate for the nanowire 601. Electrical contacts 602 fabricated in etched groves on either side of the nanowire 601 are used to apply a voltage to the electroactive element 603. The direction of ferroelectric polarisation within the element 603 (in the case of a piezoelectric), which can be set by cooling from above the ferroelectric Curie temperature with a voltage bias applied, is transverse to the magnetic nanowire 601. With this configuration, the application of a positive or negative voltage to the gate contacts 602 results in a respectively tensile or compressive strain along the poling direction and an accompanying compressive or tensile strain along the direction of the wire 601. This strain is transmitted to the magnetic nanowire 601, which is made from a magnetostrictive material, and so the

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magnetic anisotropy in the strained region will change in response to the strain. For a material with a positive magnetostriction constant, a compressive strain in the poling direction will increase the energy of a domain wall in that region of the nanowire. The graded etch depth and slanted arrangement of the voltage contacts creates a gradient in the strain profile, and also in the magnetic anisotropy energy along the nanowire. The strain profile determined by micromechanical calculations for a voltage bias of 1V applied to the gate contacts 602 on a PMN-PT substrate indicates a maximum strain of around 1.5×10^{-3} at one end of the nanowire 601. The strain profile as a function of the distance along the nanowire is shown in figure 6b. This illustrates the presence of a strain gradient along the wire of order $10^{-3}/\mu\text{m}$, which will translate to a gradient in the energy of a magnetic domain wall. This induces the magnetic domain wall to move along the nanowire to minimise its energy. The arrangement of the gates along the sides of the wire will allow several domain walls to be moved along the wire simultaneously with a single voltage pulse, which is particularly relevant for developing a shift register type memory. Also, the strain profile does not produce a local minimum in the anisotropy energy, which would trap a domain wall. Therefore, once the domain walls move beyond the region of the shift gate they are free to continue moving under their own inertia until stopped by viscous forces, or by design at a subsequent set of electrodes. This will allow the domain walls to be moved much further than the region occupied by the shift gates. Preliminary micromagnetic calculations confirm the feasibility of the shift gate concept.

Device Fabrication

To maximise the effectiveness of the technique, a substrate possessing a large piezoelectric coefficient may be used together with magnetic nanowires fabricated from materials with large magnetostriction coefficients. The piezoelectric substrate may for example be single crystal PMN-PT $[\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3]_{(1-x)}\text{--}[\text{PbTiO}_3]_x$ or PZN-PT $[\text{Pb}(\text{Zn}_{1/3}\text{Nb}_{2/3})\text{O}_3]_{(1-x)}\text{--}[\text{PbTiO}_3]_x$. These materials exhibit the largest piezoelectric responses and single crystal chips can be obtained commercially. For example, the calculations in figure 6 are based upon a PMN-PT substrate poled along the (100) direction. The large piezoelectric coefficients ($d_{33}=1400\text{pC/N}$ and $d_{31}=-600\text{pC/N}$) for PMN-PT results in a mechanical strain response of order 2×10^{-3} for an electric field of 1MV/m (below the electric breakdown threshold). The active device region, of order a few microns in width, may be etched using argon ion milling to produce a mesa structure as shown in figure 6a in order to reduce clamping by the surrounding

substrate. Therefore, the maximum strain can be achieved by the application of only a few Volts to electrodes fabricated upon the mesa. Prior to fabrication, the substrate may be polished to sub-nm surface roughness to reduce possible pinning sites in the subsequent magnetic layer. The roughness can be further reduced by depositing buffer layers (e.g. Ru or Ta) prior to deposition of the magnetic layer. The magnetic nanowires and electrodes may be fabricated using magnetron sputter deposition or evaporation, combined with electron beam lithography and liftoff or ion milling. For nanowires with in-plane magnetic anisotropy, a suitable choice for a magnetic material is the highly magnetostrictive alloys Terfenol-D or Galfenol. Terfenol-D ($\text{Tb}_{0.7}\text{Dy}_{0.3}\text{Fe}_2$) exhibits the highest room temperature magnetostriction of any known alloy and sputtered polycrystalline films have been shown to have a saturation magnetostriction coefficient of $\lambda_s=320\text{ppm}$ [reference 54]. Sputtered polycrystalline films of Galfenol ($\text{Fe}_{81}\text{Ga}_{19}$) have been shown to exhibit a magnetostriction coefficient of $\lambda_s\approx 100\text{ppm}$ [reference 55]. Both materials possess favourable magnetic properties, including large magnetic moment, enabling effective design of the magnetic anisotropy by the shape of the structure, and large spin stiffness, resulting in large stable domains separated by domain walls of order 100nm in width. A material may be selected based on which produces nanowires with the fewest pinning sites (determined in part by grain size) and the highest domain wall mobility.

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Creating Domain Walls

Concepts such as the magnetic racetrack memory, magnetic logical processing devices and the three dimensional shift register based upon stacked magnetic wires all require domain walls to be created in a magnetic structure using either electrical currents to generate a magnetic field locally, or by applying an external magnetic field. No concept has been proposed to nucleate domain walls and to inject them into a magnetic wire using only electric fields.

The methods described above can be implemented in a circuit assembled out of magnetic wires to create domain walls and to inject them into a nanowire. These domain walls can then be moved into magnetic storage shift registers or magnetic logical processing circuits.

The arrangements of voltage contacts designed to move magnetic domain walls along magnetic wires, described in the previous sections, may be referred to as “shift gates”,

since they act to shift magnetic domains under control of an applied voltage. An example of a single magnetic wire 701 with multiple domains acting as a shift register 700 is shown in figure 7. At one end of the wire 701 is a domain wall injector 702, and at the other end is a readout circuit 703. A shift gate 705 comprising two electrodes 704a, 704b is provided along the wire 701. Domains within the wire 701 are represented by arrows indicating the magnetic orientation, with domain walls separating adjacent domains of different polarity. The shift gate 705 acts to move the domains along the wire 701 from the injector 702 to the readout circuit 703.

10 An example magnetic wire circuit, incorporating several sets of shift gates around magnetic wires in an arrangement designed to produce magnetic domain walls, is depicted in figure 8. As in figure 7, shift gates are represented by slating lines on either side of the magnetic wire 801, and arrows on the wire 801 represent the magnetisation direction, with regions of different magnetisation separated by domain walls. The direction of the magnetisation along particular lines of the circuit may be held fixed, or pinned, by exchange coupling to an adjacent magnetic layer possessing a large coercivity. These sections, shown by the shaded regions 802 in figure 8, may comprise either a ferromagnet (e.g. CoFe) or an antiferromagnet (e.g. IrMn) exchange coupled to the wire 801, or a synthetic antiferromagnetic structure as used in magnetic tunnel junctions [reference 27]. Exchange coupling may be achieved either by direct contact or through a thin non-magnetic spacer such as Ruthenium [reference 28].

Operation of the domain wall injector circuit may proceed according to the following sequence of events:

- 25 i) The circuit is initialised (equivalent to factory setting) by applying a magnetic field to align the magnetisation in the wire 801 from right to left. After this point no further magnetic fields need to be applied.
- ii) Voltage pulses are applied to shift gates 1, 2 and 3; domain walls are positioned at gates 4 and 5.
- 30 iii) A voltage pulse on gate 4 positions a domain wall at gates 2 and 3.
- iv) The domain wall at gate 5 can be moved down the injection line by pulsing gates 5 and 6. A further domain wall can be added to the injection line by pulsing gate 3.
- 35 v) Gates 2, 3 and 4 can be used to create more domain walls for adding to the injection line by repeating sequence steps ii), iii) and (iv).

Inducing a sufficiently large contribution to the magnetic anisotropy energy in a continuous region of a wire, or stack of wires, favouring different orientation of the magnetisation than in the unaffected regions of the wires, results in the formation of magnetic domains. In a system with multiple magnetic easy axes, the newly formed domain can persist after switching the applied voltage off when its magnetization rotates to an easy axis misaligned with the initial magnetization. For example, ferromagnetic or antiferromagnetic systems with dominant intrinsic in-plane cubic anisotropy develop domains with magnetization differing by 90° .

Operation of the above type of device relies on the ability to send domain walls from one wire along two separate wires simultaneously. This process has been demonstrated to work previously in a “fan out” structure [reference 50]. Another feature is that, once propelled by the shift gates, domain walls will move under their own inertia until they reach the next set of shift gates. It has also been observed that domain walls can move several micrometres along nanowires under their own inertia. Such distances are more than sufficient for the circuit design presented here, which has a total length of only a few micrometres.

Once injected into the shift register, the domain walls can be moved along the wire simultaneously by a voltage pulse to the single set of shift gates. This way, it should be possible to transport entire bit lines (sequences of domain walls) whilst retaining the sequence structure. Once the bit line is in the shift register it will be stored until required for readout.

Detecting Domain Walls

Readout of the information can be achieved by moving the domain walls from the shift register into a section of wire with adjacent voltage contacts fabricated on top of the piezoelectric substrate. At each clock cycle, the voltage pulse to the shift gates will propel a domain wall through the readout section. The direction of the magnetisation within the domain wall will create a strain locally through the magnetostriction effect. Micromechanical calculations predict that the magnitude of the strain will be sufficient to produce a detectable voltage pulse of order $100\mu\text{V}$ on the readout gates.

A moving domain wall in a magnetostrictive wire, or stack of wires, on a piezoelectric substrate can be detected using the voltage induced as the local lattice deformation

accompanying the domain wall passes by a pair of contacts attached to the piezoelectric substrate in a position close to the wires. Using slanted contacts larger than the domain wall width allows for detection of a sequence of domain walls at once and for a longer detection time window than for a narrow contact arrangement.

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Electrical contacts to a magnetic nanowire, positioned before and after the shift gate, can be used to detect the presence of the domain wall. A magnetic domain wall is known to produce a change in the electrical resistance of the nanowire, which can be detected between the electrical contacts to locate the region in which the domain wall resides. The domain wall can be created either by applying a magnetic field to a relatively large reservoir section with low coercivity or by passing an electrical current pulse through a wire bridge over the magnetic nanowire. The magnetic field produced by the current pulse reverses the magnetisation in the region of the nanowire close to the bridge, and sequences of domain walls can be created by reversing the direction of current flow. The domain walls can then be positioned in the region of the shift gates by applying a magnetic field or by spin transfer torque (STT) due to a current applied to the nanowire. Electrical measurement techniques may be complemented by techniques to image the domain walls. Magnetic force microscopy (MFM) images of the nanowire can image the position of a domain wall before and after voltage pulses to a shift gate. Magneto-optical Kerr effect (MOKE) can also be used to detect the position of the domain walls. This technique involves positioning a laser spot at a known position on the nanowire and detecting the change in the polarisation of the light as the domain wall passes the spot. Spatial resolution on the micrometre scale can be achieved and time resolution on the nanosecond scale can be achieved by recording the output with a fast photodiode (<1ns rise time) connected to a fast (several GHz) oscilloscope.

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Performance Comparisons

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Table 1 below shows that for operations involving single bits of information, the concept described above is expected to be highly competitive in terms of both data rate and energy consumption. All other types of RAM must compromise one of these factors to optimise the other. For example, the proposed concept implemented as a racetrack is expected to be competitive with present technologies in terms of data rate, which will be limited primarily by the domain wall velocity. Micromagnetic calculations predict domain wall velocities of 100s of metres per second. As an

- example, the capacitance of a layer of PZT (lead zirconate titanate, a common piezoelectric material) with dimensions $1\mu\text{m} \times 1\mu\text{m} \times 1\mu\text{m}$ has a capacitance of order of 10^{-14} F, giving a RC time constant of order 10^{-13} s in a 50Ω circuit. This represents an upper bound since the device dimensions in this proposal will typically be smaller than this estimate. Therefore, the response time of the device is limited more by the DW velocity which can reach 1000 ms^{-1} . The data rate in Table 1 is based upon a prudent estimate of 500ms^{-1} and a domain wall separation of 500nm , although it is known that domain wall velocities can exceed 1000ms^{-1} [reference 44]. However, the greater gain comes in terms of energy efficiency. The energy per operation is determined mainly by the energy to strain the piezoelectric material. The proposed concept is expected to offer even greater gains than shown in the table because a single gate operation can act simultaneously on several domain walls. Therefore, an optimised design will process an entire bit-line (series of bits, or domain walls) in a single gate operation. This analysis shows that the concepts described herein are expected to lead to significant improvements on existing and developing RAM designs. When applied to 3-dimensional architectures, orders of magnitude improvements in storage density will be enabled, going well beyond the limits faced by current technology.
- The estimated storage density for the proposed racetrack is based upon a planar design. When extended to 3D, as proposed in the original racetrack design or a chiral soliton design [reference 6], at least an order of magnitude increase in storage density is expected to be achieved.

	DRAM	SRAM	Flash-NAND	FeRAM	MRAM	STT-MRAM	Racetrack	Proposed racetrack
Data rate (MB/s)	100	1000	20	20	50	300	500	1000
Energy per operation (pJ)	5	5	0.01	0.03	70	0.1	2	0.01
Storage density MB/inch ²	20,000	200	1000	10	16	1000	1000	1000

Table 1 - A comparison of the performance of EMAG racetrack memory with other types of RAM.

Logical Processing Devices

- Schemes for carrying out logical processing operations using magnetic nanowire circuits have been put forward [references 28, 50 & 65]. These designs all require the

application of electrical currents or magnetic fields to move magnetic domain walls through the circuit. Using techniques disclosed herein, magnetic nanowire circuits can be developed to perform logical processing operations using electrically controlled shift gates to move domain walls, thereby eliminating the requirements of electrical current or magnetic field from these designs. As an example, figure 9 presents a schematic diagram showing the layout of a logical OR gate. The initial state has the magnetisation pointing from right to left everywhere. The input lines are from the preceding logical circuit elements, or storage registers. Information can be represented as logical “1” for either the presence of a domain wall or for the magnetisation pointing from left to right. Logical “0” is then the absence of a domain wall or magnetisation pointing from right to left. A logical “1” on either of the input lines will require a domain wall to be injected into that line. Pulses on the shift gates will push the domain wall(s) onto the output line switching the output state to logical “1”. Variations on this circuit, combined with the domain wall injectors described herein can be used to construct the circuits to perform AND, NOT and XOR operations, thereby representing a complete set required for all necessary logical operations.

Nanowires with Perpendicular Magnetic Anisotropy (PMA)

The same principles described above are also applicable to materials with PMA, where the stronger anisotropy energy tends to produce narrower domain walls which can be spaced more closely. This will be advantageous for device applications as it will lead to higher storage densities and smaller device dimensions.

A question that arises in relation to materials with PMA is how effective the anisotropy gradients can be in moving domain walls in PMA materials. An additional complication is that domain walls in PMA materials can have two possible configurations depending upon whether the magnetisation within the domain wall rotates within the plane of the magnetisation (Néel wall) or perpendicular to it (Bloch wall). The application of an in-plane magnetic anisotropy by electric field-induced strain will alter the relative stability of the two types of domain wall and may lead to a transformation of the wall structure, i.e. it may induce Walker breakdown of the domain wall motion. On the other hand, if one type of domain wall is much more stable than the other, the anisotropy gradient will not lead to this transformation and will induce uniform motion of the domain wall.

Materials with PMA that may be suitable include multilayers of Ni/Co or Co/Pt [references 66, 67]. For a large magnetostrictive response it will be beneficial to use $\text{Co}_{60}\text{Fe}_{40}$ in place of Co. This particular composition may be selected because it has the maximum magnetostriction of the $\text{Co}_x\text{Fe}_{1-x}$ family of alloys. An in-plane magnetic anisotropy energy component can be introduced to favour either a Bloch or Néel type domain wall by sputtering the material in a magnetic field or by poling the direction of the electroactive substrate after deposition of the magnetic film to introduce a permanent offset strain.

10 An alternative method to induce PMA is to grow ultra-thin Fe based alloys with an oxide interface, e.g. Fe/MgO or FeCo/MgO. The application of an electric field across the interface has been shown to tune the PMA energy in such systems. This raises the intriguing possibility of combining the effects of the electric field gating of the metal/dielectric interface with electric field-induced strain from the electroactive element. The voltage applied to the FeCo/MgO interface will strengthen or weaken the PMA and so decrease or increase the width of the magnetic domain walls. There is therefore an interplay between the strength of the PMA, as tuned by the voltage applied to the FeCo/MgO interface, and the effectiveness of the strain induced anisotropy gradient to move magnetic domain walls. Although technically challenging because of the possibility of strong domain wall pinning in the ultrathin films, this additional degree of freedom may open up new avenues for tuning the motion of domain walls in materials with PMA and may lead to even greater efficiencies in the operation of the devices described herein. Inducing PMA at a $\text{Fe}_{81}\text{Ga}_{19}$ /Oxide interface may also be investigated. This would allow both methods of electric field control of anisotropy (interface gating and electric field-induced strain) to be implemented in the same highly magnetostrictive material. The metal/oxide interfaces may be formed using high-k dielectric layers with low defect density. These may be grown by atomic layer deposition.

30 Stacked Coupled Magnetic Layers

The methods for creating gradients in the mechanical strain can be implemented in device designs based upon a concept for 3-dimensional storage devices consisting of stacks of thin ferromagnetic layers separated by non-magnetic spacer layers. The magnetic coupling between adjacent ferromagnetic layers can be tuned by the thickness of the spacer layer and can be ferromagnetic or antiferromagnetic.

Information is stored in the form of a magnetic domain wall (also referred to as a soliton), represented by a sharp break or continuous rotation in the ordering of the magnetic layers along the stack. The magnetic layers can have any cross section that will produce a uniaxial magnetic anisotropy in the plane of the magnetic layer (e.g. elliptical).

The stack can be positioned on top of an electroactive substrate. Voltage contacts can be positioned on the substrate on either side of the magnetic stack, such that the ferroelectric polarisation of a piezoelectric material (if chosen as the electroactive material) is aligned in the direction from one voltage contact to the other. The magnetic easy axes of the individual magnetic layers within the stack lie in the direction perpendicular to the ferroelectric polarisation. A possible arrangement is depicted in the device 1000 shown in figure 10, in which a stack 1001 comprising alternating magnetic and nonmagnetic layers is mechanically coupled to an electroactive element 1002. Electrodes 1003 are provided on the electroactive element 1002, the electrodes 1003 being aligned in a direction parallel to the plane of the layers of the stack 1001 to provide a strain gradient between the base layer (i.e. the layer closest to the electroactive element 1002) and the top layer (i.e. the layer furthest away from the electroactive element 1002) of the stack 1001 to cause movement of a domain wall between layers of the stack 1001.

A voltage applied to the voltage contacts 1003 will induce a mechanical strain at the base of the magnetic stack structure 1001. The strain will be transmitted up the stack 1001, and will become weaker as a function of distance up the stack 1001 due to relaxation. Therefore, a gradient in the strain will be created along the length of the stack 1001. This will create a gradient in the magnetic anisotropy energy in successive magnetic layers within the stack 1001. A soliton formed in the stack 1001 and consisting of one or more magnetic layers with the magnetisation rotated away from the magnetic easy axis can thereby be moved up or down the stack in response to this strain gradient.

A modification of the above design could be to cap the top of the stack 1001 with a stiffer material (i.e. a material with a Young's modulus higher than that of the stack material). This will reduce the response of the top layer of the stack to the strain induced in the bottom layer, thereby enhancing the gradient in the strain along the

stack. Another modification could be to position the stack 1001 upon a mesa fabricated in the substrate 1002. This will increase the strain that can be induced at the bottom of the stack 1001 by reducing clamping of the piezoelectric material to the surrounding substrate. Another modification could be to position the voltage contacts 1003 on the sides of the mesa in the piezoelectric substrate to increase the depth to which the electric field penetrates the mesa and so to increase the strain response of the mesa.

The magnetic layer at the bottom of the stack 1101 can be extended laterally into a wire arrangement, as depicted in the device 1100 shown in figures 11a (in side view cross section) and 11b (in plan view). A pair of shift gates 1104 positioned on either side of the stack 1101 can be used to move a magnetic domain wall 1114 back and forth between one or more wires 1102 aligned along an axis extending between the electrodes of the shift gate 1104 and disposed between the base layer 1106 of the stack and the substrate 1107, thereby writing the magnetic state of the central region of the bottom layer of the stack 1101. This will induce a soliton in the layers above the bottom layer 1106 which can be moved up the stack 1101 using the methods described above by applying a voltage across the electroactive element 1107 using electrodes 1108a, 1108b on either side of the stack 1101.

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In the device in figure 11, magnetic layers 1112 in the stack 1101 are separated by non-magnetic spacer layers 1113. The arrow 1110 indicates the poling direction of the ferroelectric PMN-PT substrate. Arrows in the magnetic layers 1112 indicate the direction of magnetisation. The stack 1101 in figure 11a is capped with a top layer 1109 of a higher modulus material to enhance the strain gradient between the top layer 1109 and the bottom layer 1106.

A domain wall 1105 within the stack 1101 will be formed by rotation of the magnetisation over approximately 5 successive layers (the number of which will depend upon the relative strength of the interlayer coupling and the anisotropy energy in each layer) and the domain walls will be separated by regions of uniform magnetisation occupying approximately 5 layers. Therefore, an 8-bit storage register will have a depth of a few hundred nanometres. The stack 1101 may be fabricated by sputter deposition or evaporation on top of a mesa formed in a piezoelectric substrate 1107 by ion milling. The bottom layer 1106 of the stack may extend into a short

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lateral wire 1102 to allow the magnetic state of the bottom magnetic layer 1106 to be manipulated in order to write information into the stack. The top section view is shown in figure 11b. Initially, the magnetic state of the bottom layer 1106 will be reversed by moving a domain wall from the lateral wire 1102 through the stack 1101 by applying a magnetic field or via spin transfer torque (STT) by passing an electrical current through the bottom layer 1106. The tapered lateral wire structure ensures that a domain wall is always present at one of the sides of the bottom layer 1106, which may be in the form of an elliptical section. This will create a domain wall *within* the stack 1101 as the magnetisation in successive layers rotates and points away from the long axis of the ellipse (the easy direction). The domain wall 1105 can be moved up the stack by increasing the applied magnetic field or via STT by passing an electrical current along the length of the stack 1101. The presence and position of a domain wall 1105 in the stack 1101 may be detected by measuring the magneto-optical Kerr effect (MOKE) signal which will vary in magnitude, due to the penetration depth of the light, as the domain wall moves through the stack structure. Alternatively, the position of the domain wall may be determined by measuring the electrical resistance of the stack, or the change in the electrical resistance in response to the voltage applied to the electrodes.

Once created, a domain wall 1105 can be moved up or down the stack 1101 by creating an anisotropy gradient along the stack 1101. This can be achieved by applying voltage pulses to the gates 1108a, 1108b along the sides of the piezoelectric mesa. The mesa structure ensures that the strain generated in the piezoelectric is maximised by reducing clamping to the surrounding substrate. The strain will be largest in the bottom layer 1106 of the magnetic stack 1101. The stiff material (high Young's modulus) at the top of the stack will clamp the top layer thereby minimising the strain at the top of the stack 1101. This will create a gradient in the strain, and therefore in the magnetic anisotropy energy, along the length of the stack, which will cause the domain wall 1105 to propagate along the stack 1101.

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To enable writing of the magnetic state of the bottom layer 1106 without magnetic fields or electrical currents, the arrangement of shift gates 1104 can be used to move the domain wall from the lateral wire 1102 back and forth across the bottom of the stack 1101. Readout can be achieved by detecting the voltage generated on the top shift gate contacts 1104 in response to the rotation of the bottom layer 1106 as the

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domain wall 1105 within the stack 1101 is moved down to the bottom layer 1106 by the side gate contacts 1104.

5 An alternative design, as illustrated in the device 1200 shown in figure 12, would be to embed the magnetic stack 1201 into the substrate 1202. A voltage applied to the contacts 1203 on the surface of the substrate 1202 creates a gradient in the strain as a function of depth into the substrate 1202, thereby creating a gradient in the strain profile along the length of the stack 1201. A modification to this design could be to embed the magnetic stack in a mesa fabricated in the substrate. The mesa will be released from the substrate at the top, but will remain clamped to the substrate at the bottom, thereby enhancing the strain gradient produced by the voltage applied to the contacts. A further modification would be to position the voltage contacts along the sides of the mesa.

15 In an alternative design the magnetic layers may consist of antiferromagnetic or ferrimagnetic material. The ordering of the magnetic sublattices will be consistent between magnetic layers, or may change depending on the sign of the coupling determined by the non-magnetic layers. A domain wall will be represented by a rotation of the axes of the magnetic sublattices as the ordering of the magnetic sublattices changes over one or more magnetic layers. There will be an energy cost associated with the rotation of the axes of the magnetic sublattices away from the easy axes. Therefore a strain gradient, which will produce a gradient in this energy cost, can be used to move such a domain wall along the stack.

25 Magnetic Stack with Biaxial Magnetic Anisotropy

A magnetic stack structure, similar to the structure described in the preceding section, could be constructed using a material with biaxial anisotropy. In such a structure, there would be two magnetic easy axes in the plane of each magnetic layer. The biaxial anisotropy could arise from magnetocrystalline anisotropy if the material is crystalline. Alternatively, the biaxial anisotropy could be induced by the shape of the cross section of the magnetic stack structure. The strain could be generated by any of the arrangements or modifications described in the preceding section. By alternating the polarity of the voltage applied to the contacts, the magnetisation in the layers could be rotated into one or other of the biaxial easy axes, where it would remain once the strain is removed. Due to the presence of a gradient in the strain along the stack,

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the magnetisation in the layer at the bottom (in the case of the stack on top of the substrate) or the top (in the case of a stack embedded within the substrate) would rotate first because this layer experiences the largest strain. On increasing the magnitude of the voltage, the magnetisation in the next layer in the stack would rotate, then the next layer and so on. By this method, subsequent layers in the stack could be rotated. A domain wall will exist between the last layer in which the magnetisation has been rotated and the next layer in which the magnetisation has not been rotated. The direction or axis of magnetisation of the layers in the stack, or the position of a domain wall in the stack can be used to represent information. By changing the polarity of the applied voltage, the domain wall can be removed by switching the magnetisations of the layers back to their original directions or axes.

A modification to the design could be to vary the thicknesses of the magnetic layers as a function of their position along the stack. This will alter the ratio of bulk and interface contributions to the anisotropy energy in each layer, thereby altering the strain required to switch each layer. On its own, or in combination with the strain gradient, this will increase or decrease the increments in applied voltage required to switch the magnetisation of successive layers in the stack.

Another modification could be to alter the thickness and/or composition of the spacer layers to strengthen or weaken the coupling between successive magnetic layers. This will alter the strain required to switch each magnetic layer. On its own, or in combination with the strain gradient and the designs and modifications described above, this will increase or decrease the increments in applied voltage required to switch the magnetisation of successive layers in the stack.

The presence and position of a domain wall in the stack, or the directions or axes of magnetisation of the layers, may be detected by measuring the magneto-optical Kerr effect (MOKE) signal which will vary in magnitude, due to the penetration depth of the light, as the domain wall moves through the stack structure. Alternatively, the position of the domain wall, or the directions or axes of magnetisation of the layers, may be determined by measuring the electrical resistance of the stack, or the change in the electrical resistance in response to the voltage applied to the electrodes.

Magnetic Wires at an Angle to the Substrate Plane

The methods and device designs described above that relate to stacks of magnetic layers, can be applied also to continuous magnetic wires oriented at a non-zero angle to the plane of the piezoelectric substrate. The continuous wires can be fabricated on top of the substrate or can be embedded within the substrate or within a mesa fabricated out of the substrate material. A domain wall can be created within the continuous wire by rotation of the magnetisation in a section of the wire using voltage-induced strain. A gradient in the anisotropy energy, created by voltage-induced strain, will induce a domain wall to move along the wire such that it will minimise the energy of the system.

Lab-on-Chip Applications

Magnetic domain walls can provide localized mobile magnetic fields that may be used to trap and move organic molecules or micron-sized beads along wires [references 23, 24 and 29]. Current lab-on-chip technology uses external magnetic fields and spin transfer torque to move the domain walls. These methods can be replaced by the above described mechanism based on magnetic anisotropy gradients, offering higher energy efficiency and better control over sequences of moving domain walls.

Devices Using Temporal Changes in Magnetic Anisotropy Energy Profiles

Motion of magnetic domain walls may be induced by inducing rapid changes of the magnetic anisotropy energy in the region of the magnetic domain walls. This may be done by creating and controlling rapid changes of magnetic anisotropy energy within magnetic wires or stacks of wires. The rapid changes of magnetic anisotropy energy are used to induce motion of magnetic domain walls situated in the region of the changing magnetic anisotropy energy.

In one example, the magnetic anisotropy energy can be modified by a mechanical strain induced in the magnetic material. This may be achieved by depositing the magnetic layer on an electroactive (i.e. piezoelectric or electrostrictive) layer, or by depositing an electroactive layer on the magnetic layer. Voltage contacts fabricated on the electroactive layer may be arranged such that the application of a voltage pulse to the contacts induces a mechanical strain pulse in the electroactive layer, which is transmitted to the magnetic part of the device in which it creates a mechanical strain

pulse in a region of the magnetic wire or stack of wires. The strain produces a change in the magnetic anisotropy energy along a section of the wire or stack of wires via the inverse magnetostriction (or Villari) effect. Depending on the geometry of the contacts, the induced magnetic anisotropy energy can have a nonzero spatial gradient in part of the wire or stack of wires. In some cases the induced anisotropy energy can be homogeneous along the whole or part section of the wire or stack of wires.

In another example, the magnetic anisotropy energy may be modified by an electric field pulse applied at the interface between the magnetic layer and an insulator. Voltage contacts are placed on both the magnetic layer and the dielectric layer. Depending on the geometry of the contacts, and/or the thickness variation of the dielectric layer, the induced magnetic anisotropy energy can have a nonzero gradient in part of the wire or stack of wires. In some cases the induced anisotropy energy can be homogeneous along the whole or part section of the wire or stack of wires.

In another example the magnetic material may be deposited onto a ferroelectric layer or a ferroelectric layer may be deposited onto the magnetic layer. Alternatively, the material may consist of a single multiferroic layer possessing both electric and magnetic order parameters. Voltages applied to contacts fabricated on the ferroelectric layer cause ferroelectric domain walls to move in the ferroelectric layer. This changes the strain and/or electric field in the vicinity of a magnetic domain wall. This results in a change in the magnetic anisotropy energy in the vicinity of the domain wall. Depending on the geometry of the contacts, the induced magnetic anisotropy energy can have a nonzero gradient in part of the wire or stack of wires. In some cases the induced anisotropy energy can be homogeneous along the whole or part section of the wire or stack of wires.

In another method an electric field can be used to modify the carrier density in a magnetic material (e.g. a magnetic semiconductor - references 30, 31). This causes a change in the magnetic anisotropy energy in the vicinity of a magnetic domain wall in the magnetic material. Depending on the geometry of the contacts, the induced magnetic anisotropy energy can have a nonzero gradient in part of the wire or stack of wires. In some cases the induced anisotropy energy can be homogeneous along the whole or part section of the wire or stack of wires.

The magnetic wires and layers described here can be fabricated from ferromagnetic, antiferromagnetic, ferrimagnetic or multiferroic materials. The magnetisation can be oriented in the plane of the layers or wires, along the direction of the wires, or perpendicular to the direction of the wires. Alternatively, the magnetisation can be oriented perpendicular to the plane of the layers or wires. Magnetic domain walls can be any type of domain wall supported by the magnetisation of the wire, including but not limited to transverse 90° , 180° , 360° , vortex, Bloch and Néel walls.

Time Varying Magnetic Anisotropy Energy

Movement of magnetic domain walls may be induced using a time varying magnetic anisotropy energy. A time varying magnetic anisotropy energy acts on the magnetisation vectors like a time varying *effective* magnetic field. The effects on the magnetisation within the magnetic domain wall can be similar to the effect of applying a time varying *real* magnetic field, but the methods of producing an effective magnetic field are different to the methods of producing a real magnetic field.

In the case of ferromagnetic material a magnetic domain wall separates two regions of uniform magnetisation direction. In a region of uniform magnetisation direction, the magnetisation points along a direction which represents a local minimum in the magnetic free energy density. Within the magnetic domain wall, the magnetisation rotates continuously between the directions defined by the magnetisation in the regions of uniform magnetisation direction. Therefore, in the domain wall the magnetic free energy density is higher than in the regions of uniform magnetisation that it separates. Changing the magnetic anisotropy energy in the region of the domain wall will cause the magnetic free energy density within the domain wall to change. The magnetisation vectors within the domain wall (which vary spatially across the domain wall profile) will experience an effective magnetic field which arises from the new magnetic anisotropy contribution to the magnetic free energy. The effective magnetic field will create a torque on the magnetisation vectors within the domain wall which will precess about this effective magnetic field for a time determined by the intrinsic and extrinsic damping mechanisms in the material and device. When the precessional motion of the magnetisation vectors ceases, the angles of the magnetisation vectors within the domain wall will differ from the angles before the change in magnetic anisotropy energy occurred. The precession of the magnetisation vectors within the domain wall will be accompanied by a lateral shift of the position

- of the domain wall. The direction of the lateral motion of the magnetic domain wall will be determined by the direction of the axis of the effective magnetic field and by the sense of rotation (chirality) of the magnetisation vectors as a function of their position across the domain wall, as well as the internal angle of the magnetisation within the domain wall. The direction of the effective magnetic field may be determined by the angle of the axis of the induced strain on its own or in combination with other magnetic anisotropy (e.g. magnetocrystalline or shape-induced) and/or an external magnetic field.
- Domains and domain walls also exist in antiferromagnets and ferrimagnets, where domain walls separate regions in which the axes of the alternating spin sublattices change, or the order of the alternating sublattices changes. The axes of the magnetisation can rotate away from the easy axes within the domain wall, which will cost energy locally. The mechanism described for moving domain walls in ferromagnets by temporal changes in the magnetic anisotropy energy will also be effective for moving domain walls in antiferromagnets and ferrimagnets.

Inducing a change in magnetic anisotropy energy density using voltage induced strain

- An example device in which a change in magnetic anisotropy energy may be induced using voltage induced strain may comprise an electroactive (piezoelectric or electrostrictive) layer and a magnetic layer. The magnetic layer can be patterned into wires which can support magnetic domain walls at positions along the length of the wire. Voltage contacts can be arranged on the electroactive layer, and the direction of the ferroelectric polarisation in the case of a piezoelectric substrate can be set such that, when a voltage is applied between the contacts or between the contacts and the magnetic wire, the electric field produces a mechanical strain in the region of the magnetic wire or wire stack close to the voltage contacts. This induces a change in magnetic anisotropy energy in the region of the magnetic wire in the vicinity of the voltage contacts.

- The magnetic wire or stack can be a voltage contact, or it can be at a floating potential. It can be in direct electrical contact with the electroactive substrate or it can be separated by a thin electrically insulating layer. One example of a device configured to achieve this is shown in figure 13a and in figure 13b in sectional view.
- The device 1300 comprises a piezoelectric layer 1301 on which a magnetic wire 1302

is deposited. Electrodes 1303 are applied on opposing sides of the magnetic wire 1302, which in this example are fabricated in the same plane as the magnetic wire on the surface of the piezoelectric substrate 1301.

- 5 A modification of this design is to etch the piezoelectric layer such that the contacts can be embedded into the substrate. This is depicted in the device 1400 shown in figure 14a, and in figure 14b in sectional view. The etching reduces clamping of the mesa to the surrounding substrate 1301, thereby enhancing the magnitude of the strain induced in the magnetic wire 1302. Electrodes 1403 are deposited on the side walls on
10 either side of the wire 1302 within trenches etches into the substrate 1301. Another modification could be to fabricate the piezoelectric layer on top of the ferromagnetic layer, as performed by Lei et al. [reference 22].

- A voltage pulse applied to a single pair of contacts, fabricated in the arrangements
15 mentioned above, will propel a domain wall or sequence of domain walls along the wire. When the voltage pulse is removed, the mechanical strain and the corresponding magnetic anisotropy energy in the magnetic wire will relax towards their states before the pulse was applied. By the same mechanism described above, this will create a torque on the magnetisation vectors within the domain walls and will induce the
20 domain walls to move laterally towards their original positions.

- It may be desirable to prevent the magnetic domain walls from moving back towards their original positions when the voltage pulse is removed. This can be achieved by controlling the fall time of the voltage pulse such that the magnetic anisotropy energy
25 changes on a timescale which is long compared to the precession period of the magnetisation vectors or the decay time of the precessional motion due to damping. For example, a fall time of several tens of ns or more may be used. This will reduce the torque on the magnetisation vectors and will reduce the corresponding lateral force on the magnetic domain wall. Alternatively, or in combination with this method, the
30 magnetic wire may be fabricated with notches, anti-notches or imperfections in the wire geometry or composition which will act so as to pin the magnetic domain walls. In one design, the shape of these notches or imperfections may be such that they impede domain wall motion in one direction, but allow the domain wall to move relatively freely in the other direction [reference 32]. Then the rising voltage pulse

will move the domain wall in one direction, but the falling edge of the voltage pulse will not cause the domain wall to move back past the geometrical feature.

5 In a general aspect therefore, the applied voltage signal may be in the form of a pulse having a rise time and a fall time, the rise or fall time being less than for example 5 ns. If the rise time is less than 5 ns, the fall time may be for example greater than 5 ns, optionally greater than 10 ns. If alternatively the fall time is less than 5 ns, the rise time may for example be greater than 5 ns, optionally greater than 10 ns. The difference in rise and fall times can be used to cause movement of domain walls with
10 a net change of position along a desired direction.

A second arrangement of voltage contacts can be fabricated further along the wire to move the domain wall or walls further along by the application of a voltage pulse to the second arrangement of contacts. By selecting the polarity of this voltage pulse, it
15 will be possible to slow down or stop the moving domain wall or walls, and to cause them to move back in the opposite direction.

An extension of this design is to fabricate a sequence of independent contact arrangements along the wire with a possible partial overlap of neighbouring contact
20 pairs/arrangements. Upon sequential application of a voltage to each pair of contacts a domain wall, or a plurality of domain walls can move continuously or step-wise along the wire.

The methods described above can be applied to move domain walls in a shift register
25 based upon the racetrack concept, where the methods can replace or reduce the requirement to use electrical current to move domain walls along the magnetic wire. The methods are also applicable in the domain wall based MRAM architecture proposed by NEC Corporation, Japan [reference 33].

30 The methods described above can be applied to designs for devices to carry out logical processing operations by moving domain walls around circuits constructed from magnetic wires. There, the methods will replace or reduce the requirements to use electrical currents or rotating magnetic fields to move the domain walls.

Moving Domain Walls along Stacks of Magnetic Wires

The methods described in the preceding section can be applied to an arrangement consisting of a plurality of magnetic wires in a stacked configuration with non-magnetic spacers between the wires. The stacking direction can be perpendicular to the plane of the electroactive substrate. Several stacks can be accommodated next to each other and between the same pairs of contacts. Each wire can contain one domain wall or a plurality of domain walls.

The stack of magnetic wires can be fabricated on top of the substrate, in the position of the single wire as depicted in figures 13 and 14. Voltages applied to the electrodes induce a change in the magnetic anisotropy energy in each of the wires in the stack. Therefore, a single voltage pulse to the contacts will move a domain wall or sequence of domain walls along each wire in the stack. Domain walls can be injected into each wire within the stack independently, thereby allowing each wire to function as an independent shift register.

A modification to this design would be to encase the stack of magnetic wires with a non-magnetic material to enhance the transmission of the strain to the wires lying higher up in the stack.

Another modification would be to embed a single wire or stack of wires within the piezoelectric substrate, or to deposit the piezoelectric layer on top of the magnetic wire stack. Voltages applied to contacts in any of the arrangements described already in this document would produce a change in the magnetic anisotropy energy.

Another modification would be to embed a single wire or the stack of wires within a mesa formed in the piezoelectric substrate, with voltage contacts along the side of the mesa.

The methods described in this section can be applied to the 3-dimensional data storage concept using stacks of magnetic wires proposed by Cowburn, where they will replace the requirement to use electrical currents or magnetic fields to move domain walls along the magnetic wire.

The concept proposed by Dean et al. [reference 25], as discussed above, moves magnetic domain walls along a ferromagnetic wire by creating a minimum in the magnetic anisotropy energy between pairs of voltage contacts positioned on top of piezoelectric materials deposited on top of the wire. The domain wall is trapped in the energy minimum. The energy minimum is moved along the wire by changing the voltages on successive voltage contacts along the wire. The domain wall moves along the wire with the energy minimum. The methods described here differ in various respects. The motion of the magnetic domain wall is induced by a torque on the magnetisation within the domain wall. The torque is induced by the change in the magnetic anisotropy energy in time. It does not require an inhomogeneous magnetic anisotropy energy profile. The design presented here allows for multiple domain walls to be moved with a single voltage pulse applied to a single pair of voltage contacts. Dean's design can only move one domain wall at a time and requires multiple voltage pulses applied to multiple pairs of voltage contacts to move the domain wall along the wire. Therefore, Dean's design will be less efficient in terms of data rate and energy use. The design presented here also propels the domain walls beyond the region of the voltage contacts. The domain walls will continue to move under their own inertia until viscous forces slow them down, or until they are stopped intentionally at the next set of voltage contacts or pinning sites. In the case of Dean's design, the domain walls are stopped by the energy minima between successive voltage contacts and are not propelled beyond the region of the voltage contacts. The designs presented herein do not require minima in the magnetic anisotropy energy along the wire. Furthermore, the designs presented here allow the magnetic part of the structure to be fabricated on top of the piezoelectric substrate, thereby allowing single crystal substrates to be used to maximise the piezoelectric effect. With Dean's design there will be degradation of the performance because the piezoelectric material must be fabricated on top of the structure and so may not have such good structural and piezoelectric properties as single crystal substrates. The designs presented here can also, in some cases, allow the magnetic part of the structure and the voltage contacts to be fabricated in the same plane on top of the piezoelectric substrate, thereby making fabrication simpler and cheaper. Finally, the geometry of the contact arrangements presented here will allow the addition of further contacts along the wire, or around the stack, for the purposes of read/write operations, without disrupting the function of the contacts for moving the domain walls. This would not be possible in Dean's design because the contacts for moving the domain walls are already on top of the wire.

Inducing change in magnetic anisotropy energy density using electrical gating of a magnetic material/dielectric interface.

An alternative technique to those disclosed above is to fabricate a device in which the
5 magnetic wire 1502 deposited on a substrate 1501 has an interface with a dielectric material 1503. A contact 1504 is fabricated on the other side of the dielectric material 1503, as shown in the example device 1500 in figure 15a, also shown in sectional view in figure 15b. A voltage applied between this contact 1504 and the magnetic wire 1502 induces a change in the magnetic anisotropy energy in the region of the wire
10 1502 in the vicinity of the contact 1504. This induces motion of the magnetic domain walls in this region by the mechanism described in the preceding section. The dielectric layers and/or contacts to the dielectric layers can be arranged in a manner similar to the description in the preceding section to allow the domain wall or walls to be moved sequentially between successive contact regions. Backwards motion of the
15 domain wall or walls on removal of the voltage can be prevented using the same techniques as described in the preceding section.

In a general aspect therefore, the device 1500 may be considered to be a magnetic storage device comprising a substrate on which is disposed a magnetic wire having a
20 plurality of magnetic domains and extending along an axis, the device comprising a pair of electrodes on opposing sides of the magnetic wire, the electrodes being separated from each other by a layer of dielectric material, the electrodes being arranged such that applying a voltage between the electrodes creates an electric field between the electrodes that causes movement of the magnetic domains along the axis
25 of the wire.

In a further general aspect a method of operating a device such as the one described above may comprise applying a voltage between the pair of electrodes to generate an electric field therebetween and move the plurality of magnetic domains along the axis
30 of the wire.

Fabricating a device 1500 such as the one shown in figure 15 involves fabricating ferroelectric layers in close contact to magnetic layers. The magnetic material may be deposited onto a ferroelectric layer or a ferroelectric layer may be deposited onto the
35 magnetic layer. Alternatively, the material may consist of a single multiferroic layer

possessing both electric and magnetic order parameters. Voltages applied to contacts fabricated on the ferroelectric or multiferroic layer cause ferroelectric domain walls to move in the layer. This changes the strain and/or electric field in the vicinity of a magnetic domain wall or walls. This results in a change in the magnetic anisotropy energy in the vicinity of the magnetic domain wall or walls. This will induce motion of the magnetic domain wall or walls in this region by the mechanism described in the preceding section. The contacts to the ferroelectric or multiferroic can be arranged to allow the magnetic domain wall or walls to be moved sequentially between successive contact regions. Backwards motion of the domain wall or walls on removal of the voltage can be prevented using the same techniques as described above.

Inducing a Change in Structure of a Magnetic Domain Wall

According to another aspect of the present disclosure, a transformation in the structure of a magnetic domain wall may be induced by inducing an inhomogeneous magnetic anisotropy energy profile in the region of a magnetic domain wall. This may be used to create and control the magnetic anisotropy energy profile within magnetic wires or stacks of wires.

In one example, the magnetic anisotropy energy may be modified by a mechanical strain induced in the magnetic material. This can be achieved by depositing the magnetic layer on an electroactive layer, or by depositing an electroactive layer on the magnetic layer. Voltage contacts fabricated on the electroactive layer are arranged such that the application of a voltage pulse to the contacts induces a mechanical strain pulse in the electroactive layer which is transmitted to the magnetic part of the device, in which it creates a mechanical strain pulse in a region of the magnetic wire or stack of wires. The strain produces a change in the magnetic anisotropy energy along a section of the wire or stack of wires via the inverse magnetostriction (or Villari) effect. Depending on the geometry of the contacts and the magnetic wires, the induced magnetic anisotropy energy can have a nonzero spatial gradient in part of the wire or stack of wires.

The magnetic wires and layers described herein can be fabricated from ferromagnetic, antiferromagnetic or multiferroic materials. The magnetisation can be oriented in the plane of the layers or wires, along the direction of the wires, or perpendicular to the direction of the wires. Alternatively, the magnetisation can be oriented perpendicular

to the plane of the layers or wires. Magnetic domain walls can be any type of domain wall supported by the magnetisation of the wire, including but not limited to transverse 90° , 180° , 360° , vortex, Bloch and Néel walls.

- 5 A static or time varying magnetic anisotropy energy profile will alter the magnetic free energy within the region of the magnetic domain wall. This will alter the magnetic domain configuration corresponding to the minimum energy configuration in the region of the domain wall. The application and/or subsequent removal of the inhomogeneous magnetic anisotropy energy profile can result in a reversal of the
10 chirality (sense of rotation) of the magnetic domain wall.

The geometry of a magnetic device induces a magnetic anisotropy, sometimes known as “shape” anisotropy or “demagnetising” anisotropy or “magnetostatic” anisotropy. The combination of this geometry induced magnetic anisotropy energy and a magnetic
15 anisotropy energy produced by mechanical strain can be used to create an inhomogeneous magnetic anisotropy energy profile in the region of a magnetic domain wall.

An example device 1600, as shown schematically in figure 16, comprises a magnetic
20 domain wall 1605 in a curved section of a magnetic wire 1602. The direction of magnetism in adjacent sections of the wire 1602 is indicated by arrows 1607a, 1607b. A uniform uniaxial mechanical strain applied to the magnetic wire 1602 using an electroactive substrate 1601 will produce a uniaxial homogeneous magnetic anisotropy energy component acting on the entire section of the wire 1602. The axis of the strain
25 induced magnetic anisotropy is indicated by arrow 1606. In some sections, i.e. in section 1607a, this anisotropy adds to the geometry induced magnetic anisotropy energy to increase locally the net magnetic anisotropy energy. In other sections, i.e. in section 1607b, the strain induced magnetic anisotropy energy competes with the geometry induced magnetic anisotropy energy to reduce locally the net magnetic
30 anisotropy energy. This results in a spatially inhomogeneous net magnetic anisotropy energy profile.

In another example, shown in figure 17, the magnetic domain wall 1705 is confined to a straight section of a magnetic wire 1702 fabricated on a piezoelectric substrate 1701.
35 Voltages applied to electrodes 1703 patterned in the vicinity of the magnetic wire

1701 induce an inhomogeneous mechanical strain in that region of the magnetic wire 1701. This results in an inhomogeneous magnetic anisotropy energy along the magnetic wire 1702. A larger strain on the left hand side of the domain wall 1705 than on the right hand side will tend to cause the domain wall 1705 to move from left to right, i.e. away from the higher strain region.

Any combination of geometry induced and strain induced magnetic anisotropy energy can be used to produce an inhomogeneous magnetic anisotropy energy profile in the region of the domain wall. This will alter the magnetic domain configuration corresponding to the minimum energy configuration in the region of the domain wall. The application and/or subsequent removal of the inhomogeneous magnetic anisotropy energy profile can result in a reversal of the chirality (sense of rotation) of the magnetic domain wall.

15 A chirality-based information storage device

The concepts described above could be incorporated separately or in combination into a device to encode information in the form of the chirality of a domain wall. A voltage induced mechanical strain can be used to reverse the chirality of the magnetic domain wall and in so doing to write the information. Domain walls could be positioned along curved or straight sections of magnetic wires or stacks of magnetic wires. There could be multiple domain walls positioned on multiple curved or straight sections of magnetic wires or stacks of magnetic wires. The magnetic wires or stacks of magnetic wires can be on top of an electroactive substrate or embedded within an electroactive substrate. Electrodes can be patterned on top of the substrate or along the sides of mesas fabricated on the substrate.

Information can be read out by measuring the electrical resistance of a section of wire containing a domain wall. Alternatively, the resistance of a stack of magnetic layers, when measured in the plane of the layers or perpendicular to the plane of the layers, will depend on the relative magnetic configuration of those layers through the giant magnetoresistance (GMR) or tunnelling magnetoresistance (TMR) effects. The GMR or TMR will give rise to different electrical resistance states if the chirality of the domain walls in adjacent layers is the same or opposite. The strain induced anisotropy energy, and therefore the effect on the domain wall, will depend on the magnetic material properties and the position of the material in the magnetic stack or relative to

the voltage electrodes. Therefore, by design of these factors it would be possible to transform the domain wall structure in different layers of a magnetic stack or at different positions along a magnetic wire by the application of different voltages to the electrodes. An example of such a device is shown in figure 18, which illustrates an information storage device 1800 comprising a domain wall 1805 positioned along a curved section of a pair of magnetic wires 1802a, 1802b separated by a non-magnetic spacer layer 1804, the wires 1802a, 1802b being deposited over an electroactive substrate 1801. The strain induced magnetic anisotropy switches the chirality of the domain wall 1805 in the lower magnetic wire 1802b. The electrical resistance of the wire stack, measured in the plane or perpendicular to the stack, will depend upon the relative chiralities of the domain walls in the upper and lower magnetic layers 1802a, 1802b.

Figure 19a shows a schematic of an example device comprising a nickel ring situated on top of a PMN-PT chip. A voltage applied across the thickness of the chip generates a uniaxial strain in the plane.

Figure 19b is a schematic representation of the uniaxial strain as a function of the electric field applied to the PMN-PT.

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Figure 19c is a representation of a vortex domain wall situated in a magnetic nanowire. Arrows represent the direction of the magnetisation.

Figure 20 is a series of XMCD-PEEM images of strain-induced chirality switching in vortex domain walls. Panel sequences **a** to **e** and **f** to **j** show the evolution of a tail to tail and head to head vortex wall respectively as a function of the electric field applied to the PMN-PT. The axis of the uniaxial strain is represented by the arrow. Roman numerals correspond to the electric fields labelled in figure 19b.

Figure 21 is a series of micromagnetic simulations of a head to head vortex domain wall under the action of a uniaxial magnetic anisotropy energy. Figure 21a to e show successive switching of the chirality of the vortex wall. The transitions from panels **a** and **c** to panels **c** and **e** respectively involve the reversal of the x-component of the magnetisation in the regions marked by dashed circles in **b** and **d**. **f** and **h** show the flux closure patterns after the application of a magnetic field along the x-axis. **g** and **i**

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show the vortex domain walls after the subsequent setting of the anisotropy energy to $K_U = -3 \text{ kJm}^{-3}$. The magnetic anisotropy easy axis is indicated by the double ended arrows.

- 5 Figures 22 and 23 illustrate further series of micromagnetic simulations of domain wall movement.

Figure 24 shows an example information storage device comprising a magnetic tunnel junction structure with ferromagnetic top and bottom electrodes fabricated on a piezoelectric substrate. The bottom electrode is a highly magnetostrictive ferromagnet (e.g. nickel) in a curved geometry to support a vortex domain wall beneath the tunnel barrier. The top electrode is a ferromagnet with low magnetostriction (e.g. permalloy) in a square geometry to support a flux closure domain state.

- 15 Figure 25 shows an alternative way of switching the chirality of a vortex domain wall by applying strain locally, in which a device comprising a vortex domain wall in a nanowire is fabricated on a piezoelectric substrate. A voltage applied to the electrodes induces a mechanical strain and a uniaxial anisotropy favouring an easy axis transverse to the wire. **a**, A vortex domain wall positioned at the edge of the electrode region, is transformed to a flux closure domain pattern near the electrodes **b**. **c**, Relaxation of the induced anisotropy leads to the formation of a vortex domain wall with the opposite chirality to the initial domain wall.

The chirality of a vortex domain wall can be controlled reversibly by creating a strain-induced inhomogeneous uniaxial magnetic anisotropy energy profile in the vicinity of the domain wall. This can be achieved by positioning a vortex domain wall along the circumference of a ring structure, close to the axis of the uniaxial anisotropy. An example device 1900 shown in figure 19a comprises a piezoelectric $[\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3]_{0.68} - [\text{PbTiO}_3]_{0.32}$ (PMN-PT) (011) substrate 1901 with top and bottom electrodes, onto which is fabricated a 20nm thick Ni ring 1902 of outer diameter $7.7 \mu\text{m}$ and inner diameter $5.7 \mu\text{m}$. Application of an electric field between the top and bottom electrodes results in mechanical deformation of the PMN-PT substrate 1901 and induces a uniaxial strain of the order of 10^{-3} in the plane of the Ni ring 1902.

The application of an electric field across the thickness direction of a PMN-PT (011) substrate is known to result in a two stage reversal of the ferroelectric polarisation vector at the coercive field [reference 77]. Switching of the polarisation vector between the $\langle 111 \rangle$ directions with components pointing out of the plane is mediated by a range of electric field for which the polarisation points fully in the plane. This is accompanied by a large uniaxial strain of order 10^{-3} in the plane in a narrow range of electric field around the ferroelectric coercive field E_C , which is approximately 0.18 – 0.19 MV/m for the device shown in figure 19a. This results in a uniaxial anisotropy energy of order 10 kJm^{-3} . Further increases of the electric field results in the strain returning to a value close to that at zero field as the ferroelectric vector rotates out of the plane towards the $\langle 111 \rangle$ directions. The sequence of magnetic contrast images in figure 19b reveals that this transition is accompanied by a reversal of the vortex wall chirality. Figures 20 a and b show the transition from a clockwise tail-to-tail wall to an anti-clockwise tail-to-tail wall at electric fields illustrated by points (i) and (ii) in figure 19b. The same transition occurs between figures 20d and e for the opposite sign of applied electric field (corresponding to (iv) and (v) in figure 19b), but an identical uniaxial strain transition. The intermediate magnetic state was not captured for these transitions because the size of the applied electric field increments was too large resulting in the uniaxial strain state being induced and removed between successive images. An intermediate magnetic state can be observed in figure 20c when the electric field had been increased further beyond the ferroelectric coercive field to point (iii) in figure 19b. Here a reversible uniaxial strain is also present, albeit smaller than that generated at the ferroelectric coercive field. Removal of this uniaxial strain results in the switching of the vortex wall chirality, from anti-clockwise to clockwise in the sequence from figures 20b to d. To summarise, figures 20a to e show that three successive applications of a uniaxial strain induce three successive reversals of the vortex wall chirality. The chirality switching is also observed for a head-to-head vortex wall shown in figures 20f to j, but the sequence is interrupted by the movement of the domain wall along the circumference of the ring in figures 20h to j. The importance of pinning of the domain wall position will be discussed in the next section.

A full understanding of the mechanism by which the vortex domain wall chirality switches would require knowledge of how the strain profile varies, both spatially and temporally. The structure of ferroelectric domains in PMN-PT and the processes

involved in switching of the ferroelectric polarisation vector are areas of intense research at present. It is known that domains can range in size from tens or hundreds of nm up to several tens of μm and that different domain regions can represent different polarisation vectors as well as different structural phases because the

5 $[\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3]_{0.68}-[\text{PbTiO}_3]_{0.32}$ composition sits close to a morphotropic phase boundary. The application of an electric field can induce reorientation of nanoscale domains and movement of the boundaries of micron scale domains within the same sample. For our sample we cannot image the ferroelectric domain structure because the presence of the top electrode prevents penetration of the x-rays to the PMN-PT. We

10 can, however consider the extreme cases: (i) the strain in the region of the vortex domain wall switches homogeneously (e.g. via the reorientation of nanoscale ferroelectric domains of size much smaller than the vortex domain wall) and (ii) the change in strain sweeps across the device (e.g. due to a ferroelectric domain wall moving across the region beneath the vortex domain wall). We find that both

15 mechanisms can induce switching of the vortex wall chirality.

The strain in the region of the vortex domain wall switches homogeneously

We performed micromagnetic simulations using the OOMMF simulation package [reference 59]. Details of the parameters used in the simulations are given below.

20 Results from the simulations presented in figures 21a to e show successive switching of vortex wall chirality from anticlockwise to clockwise and back to anticlockwise. The switching events are induced by the application of a uniaxial magnetic anisotropy favouring an easy axis perpendicular to the circumference of the ring in the vicinity of the domain wall, i.e. along the y-axis. The anisotropy causes a flux closure domain

25 pattern to form, characterised by the triangular regions 2101, 2102 in figures 21b and d, in order to minimise the magnetic free energy. There are similarities between these patterns and the experimental image in figure 20c. Crucially, the final position of the flux closure pattern in figures 21b and d is offset slightly to the right or left of the axis of the anisotropy depending upon the initial chirality of the domain wall. When

30 the anisotropy is changed to an easy axis tangential to the ring in the region of the domain wall (i.e. parallel to the x-axis), the flux closure pattern evolves back to a vortex domain wall, with the opposite chirality to the original state.

We now examine in detail the important transitions involved in this process. In Figure

35 21a the initial vortex domain wall state is made to resemble that in the experimental

images, in particular the “s-shape” of the central region 2103, by applying a uniaxial anisotropy of $K_U = -3\text{kJm}^{-3}$ parallel to the x-axis. Here the minus sign denotes the axis of the anisotropy. A small uniaxial anisotropy could arise during fabrication of the rings due to different thermal contraction of the Ni and PMN-PT, or due to the

5 ferroelectric domain state prior to electric field poling. Upon the application of a uniaxial anisotropy of $K_U = +10\text{kJm}^{-3}$ along the y-axis, also represented by the dashed line in figure 21, the flux closure pattern forms by reversing the direction of magnetisation in a region on the inner circumference of the ring, indicated by the dashed circles in figures 21b and d. The position of the reversed region depends upon

10 the initial chirality of the domain wall, such that the flux closure pattern is made up of two vortex cores – one from the original domain wall and one formed when the magnetisation in the region indicated by the dashed circle reverses. In our simulation, the reversal occurs by the precessional dynamics of the magnetisation, which is triggered by abruptly changing the anisotropy, and allowed to proceed by the realistic

15 damping coefficient used ($\alpha = 0.02$). In the laboratory experiment, we do not know the timescale over which the anisotropy changes. This will likely be governed by the reorientation of ferroelectric domains or the movement of ferroelectric domain walls between pinning sites triggered by thermal activation. If the anisotropy changes on a timescale that is long compared to the damping of the magnetisation (a few ns), then

20 the reversal of the magnetisation can still occur through thermal activation of the magnetisation precession. The OOMMF simulation package models magnetisation dynamics at zero temperature, so we have not investigated such processes. In either case (fast change of anisotropy or thermal activation of magnetisation precession), once the region indicated has reversed, then the flux closure pattern oscillates along

25 the circumference of the ring and settles to the final position on a timescale of several ns. The formation of the reversed region causes an initial rapid movement of the pattern left or right as the vortex cores gyrate. The direction of this initial motion is determined by the initial chirality of the domain wall. The final offset of the flux closure pattern along the ring is determined by this initial motion of the vortices, after

30 which damping of the magnetisation reduces subsequent oscillations. Upon setting the anisotropy back to $K_U = -3\text{kJm}^{-3}$ the formation of the vortex wall proceeds by domain wall motion resulting in the annihilation of the inner triangular region adjacent to the region marked by the dashed rings in figures 21b and d. For these transitions to the single domain wall states the damping parameter was set to a large value ($\alpha = 0.5$) to

35 suppress motion of the domain wall around the ring. If a more realistic value for the

damping parameter is used ($\alpha=0.02$) then the domain wall moves around the ring by 90° . Experimentally, we do not observe such motion due to pinning of the domain wall, likely by material defects or edge roughness. The exception to this is the sequence in figures 20h and i. Previous studies of vortex domain walls in Ni-
5 ring/PMN-PT devices observed rotation of the domain wall position by 90° around the ring, but did not report switching of the chirality.

The sequences in the simulations are deterministic. The initial wall chirality determines the offset of the flux closure pattern which in turn determines the chirality
10 of the newly formed domain wall. In real devices the final position of the flux closure pattern will depend on several factors including the ring dimensions, edge roughness, the size of the induced strain and material parameters such as the magnetisation and damping. Such factors may introduce some stochasticity into the magnetisation dynamics which could prevent repeatable switching of the chirality. A detailed
15 investigation of the influence of such factors is beyond the scope of the present work. It would be possible however, to determine the chirality of the domain wall by setting the offset of the flux closure pattern using an external impetus, such a weak magnetic field pulse, or an electrical current pulse. Figures 21f and h show the flux closure pattern after the application and subsequent removal of a 1mT magnetic field along
20 the x-axis. The flux closure patterns are offset to the opposite side of the strain axis compared to those in figures 21b and d, before the magnetic field pulses. Upon setting the anisotropy to -3kJm^{-3} (figures 21g and i) the resulting vortex wall chirality is opposite to the state that would have been achieved without applying the magnetic field pulse. Therefore, the final chirality of the vortex domain wall can be determined
25 by controlling the offset of the flux closure pattern by an external means.

Magnetic vortex domain wall chirality switching induced by a slowly sweeping strain profile

The micromagnetic simulations presented in the previous section consider the case
30 where a homogeneous uniaxial strain is applied on timescales short compared to the magnetisation dynamics. It is postulated that the same results would be obtained if a homogeneous strain profile was applied on timescales longer than the magnetisation dynamics if thermal activation was responsible for triggering switching of the magnetisation in certain regions of the device. Here we consider an alternative
35 scenario in which the uniaxial strain is swept from one side of the ring structure to the

other on timescales long compared to the magnetisation dynamics. This might occur for example via the voltage-induced motion of a ferroelectric domain wall in the electroactive layer which can create a strain profile that varies both spatially and temporally in the region of the vortex magnetic domain wall. This will occur if the mechanical strain has a different magnitude and/or axis in the regions on either side of the ferroelectric domain wall, or if the strain in the region of the ferroelectric domain wall has a different magnitude and/or axis compared to regions some distance away from the region of the ferroelectric domain wall. Micromagnetic simulations were performed using OOMMF with the same parameters as described in the previous section. The damping parameter was set at $\alpha=0.02$ to simulate realistic damping. A uniaxial anisotropy energy of magnitude $K_U=10\text{kJm}^{-3}$ was applied to one region of the structure, the size of which was increased in $0.1\mu\text{m}$ increments with the magnetisation dynamics allowed to damp fully at each increment. This would represent a slowly creeping strain profile, such as might occur due to the motion of a ferroelectric domain wall on timescales long compared to the magnetisation dynamics. The sequences in Figure 22a show the results of simulations as the uniaxial anisotropy is swept from left to right. As the boundary between the regions with different anisotropy approaches the vortex domain wall, the wall suddenly moves towards the boundary and is absorbed by the high anisotropy region, reversing its chirality in the process. The switching of the chirality occurs because the magnetisation on the left hand side of the vortex domain wall has a component along the y-axis that is antiparallel to the corresponding component of magnetisation *within* the left hand side of the wall. This situation is energetically unfavourable and the total energy of the system is reduced by the switching of the vortex wall chirality. Consistent with this interpretation are the results of sweeping the anisotropy from right to left, as shown in Figure 22b. The magnetisation on the right hand side of the vortex domain wall has a component along the y-axis that is parallel to the magnetisation within the wall. This situation is energetically favourable and so the chirality of the domain wall does not switch.

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Figures 23a and 23b show the results of reducing the anisotropy. Starting with the final state from Figure 22a, the anisotropy is reduced to $K_U=-3\text{kJm}^{-3}$ (i.e. an easy axis parallel to the x-axis) in regions spreading from right to left (Figure 23a) or from left to right (Figures 23b). In Figure 23a the chirality of the vortex domain wall is retained, where as in Figure 23b the chirality switches once again. In both cases the

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vortex domain wall moves with the boundary separating the regions with different anisotropy.

The results of the simulations presented in this section reveal a mechanism by which a spatially and temporally varying strain profile can be used to control both the chirality and position of a vortex domain wall. Sweeping the strain across the device along other directions, for example from top to bottom, may also induce switching of the chirality of the domain wall.

Having developed an understanding of the mechanism by which the vortex wall chirality can be switched reversibly and deterministically by voltage induced strain, we propose in figure 24 a device concept based upon the MRAM concept, but using the vortex wall chirality to encode information. The device 2400 consists of a curved section of wire 2401 fabricated from a highly magnetostrictive ferromagnet on top of a piezoelectric or electrostrictive substrate 2402. A magnetic tunnel junction structure 2403 (insulator/ferromagnet) is positioned over a section 2404 of the wire 2401 where a vortex domain wall 2405 forms. A top section 2406 of the structure 2403 consists of a ferromagnet with low magnetostriction (e.g. permalloy), fabricated into a square or circular geometry such that it will support a flux closure domain pattern which will be insensitive to the voltage induced strain. When the chirality of the vortex domain wall 2405 is the same as the chirality of the flux closure pattern in the upper layer 2406 the tunnelling resistance will be low. When the chiralities in the two layers 2406, 2404 are opposite the tunnelling resistance will be high. The switching of the vortex domain wall 2404 chirality can be achieved by applying voltage pulses to the piezoelectric substrate 2402. The proposed device concept has two significant advantages over commercial MRAM. In commercial MRAM the magnetisation is switched using electrical current via the spin transfer torque mechanism. Power dissipation due to Joule heating and stray magnetic (Oersted) fields generated by electrical currents place limits on the energy efficiency and packing density of the devices. As shown by Hu et al [reference 74], the use of electric fields to switch MRAM devices leads to orders of magnitude reductions in energy per switching event and avoids the generation of Oersted fields. Also, the vortex configurations in our proposed device minimise stray fields from the magnetic elements, thereby reducing interactions between neighbouring components leading to higher possible packing densities.

We extend our understanding that an inhomogeneous magnetic anisotropy can be used to switch the chirality of a vortex domain wall to consider a device geometry that can allow the chirality of a vortex domain wall in a straight nanowire to be reversed by a uniaxial strain applied locally. Figure 25 shows a schematic layout of a device 2500 comprising a ferromagnetic Ni wire 2501 on a piezoelectric substrate 2502 with voltage gate electrodes 2503 positioned on either side of the wire 2502 to produce a strain in a local region along the wire 2501. Such an arrangement would produce a uniaxial anisotropy if patterned on a PMN-PT (001) substrate. The sequence of images from micromagnetic calculations in figures 25a to c show that a uniaxial anisotropy applied transverse to the wire 2502, with a vortex wall positioned at the edge of the strained region, induces the formation of a flux closure pattern similar to that observed in the rings. Relaxation of the anisotropy leads to the formation of a vortex wall with the opposite chirality to the original wall. This functionality could be included in a scheme for logical processing using vortex domain walls. A gate design that produces an anisotropy gradient may also be used to move the domain wall along the wire. A device design may therefore be envisaged in which a succession of gates are implemented to move and switch the chirality of vortex domain walls, which would avoid the need to use magnetic fields or electrical currents in information processing schemes using domain walls, thereby removing some of the major practical limitations to the development of such technologies.

In conclusion we have shown that the chirality of a magnetic vortex domain wall can be switched reversibly by inducing a magnetic anisotropy profile in the vicinity of the wall. Our experimental demonstration utilises the uniaxial magnetic anisotropy energy induced by inverse magnetostriction in a hybrid piezoelectric/ferromagnet device, combined with the shape anisotropy of a ferromagnetic ring. We propose a device for information storage based on a magnetic tunnel junction similar to MRAM technology, and our concept can be extended to switch the chirality of vortex domain walls in magnetic nanowires by applying voltages locally. Methods to control magnetic domain walls deterministically using electric fields will allow the design of practical low energy devices for information and communications technologies.

Methods

10mm x 10mm x 0.5mm PMN-PT(110) substrates were purchased from Atom Optics Co., Ltd. Atomic Force Microscopy measurements revealed a surface roughness of

order 1nm. Ti(5nm)/Au(35nm) electrodes were deposited onto the top and bottom sides of the PMN-PT by thermal evaporation. The ring pattern was defined using electron beam lithography before deposition of Ni(20nm)/Al(2nm) by magnetron sputtering followed by lift-off.

5

Magnetic contrast images were obtained using the X-ray Photoemission electron microscope (PEEM) on beamline I06 at the Diamond Light Source synchrotron. Illuminating the sample at oblique incidence and making use of XMCD at the Ni L_3 edge as the contrast mechanism allowed sensitivity to in-plane moments with a spatial resolution of approximately 50nm. Azimuthal rotation of the sample with respect to the incident polarization vector allowed unambiguous assignment of the magnetization direction in each domain. Additional electrical feedthroughs allowed the in-situ application of voltage to the PMN-PT whilst imaging.

15 Micromagnetic simulations were carried out using the Object Oriented Micromagnetic Framework package¹⁹ installed on the University of Nottingham High Performance Computing cluster. Simulations were performed for a half ring geometry with inner diameter = 5.7 μ m, outer diameter = 7.7 μ m and thickness = 20nm. The mesh size was 5nm x 5nm x 20nm. Magnetisation $M=490\text{kAm}^{-1}$. The damping constant is stated in
20 the main text. The ends of the half ring section were set to critical damping to suppress the reflection of spin waves. Simulations were carried out using uniaxial anisotropy energy values of $K_U=-3\text{kJm}^{-3}$ and $+10\text{kJm}^{-3}$.

Another example device 2600 is shown figure 26. First and second electrodes 2602
25 and 2603 are positioned across the thickness direction of an electroactive layer 2601 where the electroactive layer 2601 consists of a material that produces an isotropic strain response in the plane of the layer when an electric field is applied orthogonal to the plane of the layer. The top surface of the electroactive material is patterned into a rectangular mesa 2604 and the magnetic wire 2603, representing one of the electrodes,
30 is positioned on top of the mesa with its long axis aligned to the long axis of the mesa 2604. As a result of the absence of electroactive material on either side of the mesa 2604, the rectangular mesa 2604 can expand more easily in the direction perpendicular to its width, than in the direction along its length. This results in a uniaxial strain profile along the axis of the magnetic wire, as shown by the results of

micromechanical (COMSOL) calculations in figure 27 when an electric field of $1\text{V}/\mu\text{m}$ is applied between the electrodes 2602, 2603.

5 The uniaxial anisotropy may be further enhanced if the electroactive layer consists of a material that produces an anisotropic strain response in the plane of the layer when an electric field is applied orthogonal to the layer e.g. PMN-PT [reference 75].

10 The width of the rectangular mesa 2604 may be made to vary along the axis of the magnetic wire 2602 so that a gradient of the induced strain is created along the axis of the wire caused by variation in the clamping of the electroactive element by the surrounding material.

Other embodiments are intentionally within the scope of the invention, which is defined by the appended claims.

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CLAIMS

1. A magnetic storage device comprising:
an electroactive element comprising a piezoelectric or electrostrictive element
5 having first and second electrodes arranged to apply an electric field across the electroactive element to induce a strain; and
a magnetic wire having a plurality of magnetic domains separated by magnetic domain walls, the magnetic wire aligned along an axis and mechanically coupled to the electroactive element;
10 wherein the first and second electrodes are arranged such that the electric field is aligned in a direction having a component orthogonal to the axis of the magnetic wire, a magnitude of the induced strain having a gradient along the axis of the magnetic wire to cause movement of the magnetic domain walls along the axis of the magnetic wire.
15
2. The magnetic storage device of claim 1 wherein the component of the direction of the electric field orthogonal to the axis of the magnetic wire is at least 50%.
3. The magnetic storage device of claim 1 wherein the direction of the electric
20 field is orthogonal to the axis of the magnetic wire.
4. The magnetic storage device of any preceding claim wherein the electroactive element is a substrate.
- 25 5. The magnetic storage device of any preceding claim wherein the first and second electrodes are provided on opposing sides of the magnetic wire.
6. The magnetic storage device of claim 5 wherein a distance between the first and second electrodes varies along the axis of the magnetic wire.
30
7. The magnetic storage device of claim 5 wherein the pair of electrodes are within trenches in the electroactive element.
8. The magnetic storage device of claim 7 wherein the trenches have a depth that
35 varies in a direction along the axis of the magnetic wire.

9. The magnetic storage device of any one of claims 5 to 8 comprising one or more further pairs of electrodes provided on opposing sides of the magnetic wire separated from the first and second electrodes along the axis of the magnetic wire.

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10. The magnetic storage device of any preceding claim wherein the magnetic wire is one of a plurality of magnetic wires aligned along the axis extending between the first and second electrodes, the plurality of magnetic wires being separated from each other by layers of a nonmagnetic material.

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11. The magnetic storage device of claim 10 wherein the plurality of magnetic wires is encased with a nonmagnetic material.

12. The magnetic storage device of any preceding claim wherein the magnetic wire or the plurality of magnetic wires is embedded within the electroactive element.

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13. The magnetic storage device of claim 12 wherein the first and second electrodes extend across opposing walls of the electroactive element on either side of the magnetic wire, a thickness of each wall tapering along the axis of the magnetic wire.

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14. The magnetic storage device of any preceding claim wherein the magnetic wire or the plurality of magnetic wires consists of or comprises a ferromagnetic, ferrimagnetic or antiferromagnetic material.

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15. The magnetic storage device of any preceding claim comprising a stack of alternating magnetic and nonmagnetic layers attached to the magnetic wire and the electrostrictive element between the first and second electrodes.

16. The magnetic storage device of any preceding claim wherein the or each magnetic wire is between 10 and 100nm in width and 1 μ m or more in length.

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17. The magnetic storage device of any preceding claim wherein one of the electrodes comprises the magnetic layer.

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18. A method of operating a magnetic storage device, the device comprising:
an electroactive element comprising a piezoelectric or electrostrictive element having first and second electrodes for applying an electric field across the electroactive element to induce a strain; and
5 a magnetic wire having a plurality of magnetic domains separated by magnetic domain walls, the magnetic wire aligned along an axis and mechanically coupled to the electroactive element,
the method comprising applying a voltage signal between the first and second electrodes to generate an electric field across the electroactive element that generates
10 an induced strain in the magnetic wire, the voltage signal having a temporal profile sufficient to cause the plurality of magnetic domain walls to move along the axis of the wire.
19. The method of claim 18 wherein the voltage signal is applied between the first
15 and second electrodes as a pulse having a rise time or fall time of less than 10 ns.
20. The method of claim 18 or claim 19 wherein a magnitude of the strain has a gradient along the axis of the magnetic wire.
- 20 21. The method of any one of claims 18 to 20 wherein the plurality of magnetic domain walls move at least 10 nm along the axis of the wire in response to the induced strain.
22. A magnetic storage device comprising:
25 an electroactive element comprising a piezoelectric or electrostrictive element having first and second electrodes for applying an electric field across the electroactive element to induce a strain; and
a stack of alternating magnetic and nonmagnetic layers, the stack having a base layer mechanically coupled to the electroactive element;
30 wherein the first and second electrodes are arranged such that the induced strain is aligned in a direction parallel to the plane of the layers of the stack to provide a strain gradient between the base layer and an opposing top layer of the stack to cause movement of a domain wall between layers of the stack.

23. The magnetic storage device of claim 22 wherein the pair of electrodes are within trenches in the electroactive element on opposing sides of the stack.

24. The magnetic storage device of claim 22 or claim 23 wherein the top layer of the stack consists of a material having a higher Young's modulus than the bottom layer.

25. The magnetic storage device of any one of claims 22 to 24 comprising a magnetic wire extending along an axis between the electrodes.

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26. The magnetic storage device of claim 25 wherein the magnetic wire is disposed between the base layer of the stack and the electroactive element.

27. The magnetic storage device of any one of claims 22 to 26 wherein the stack is embedded within the electroactive element.

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28. The magnetic storage device of any one of claims 22 to 27 wherein the magnetic layers consist of or comprise a ferromagnetic, ferrimagnetic or antiferromagnetic material.

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29. A magnetic storage device comprising:
an electroactive element comprising a piezoelectric or electrostrictive element having first and second electrodes arranged to apply an electric field across the electroactive element to induce a strain; and

25 a magnetic wire having first and second magnetic domains separated by a vortex domain wall, the magnetic wire mechanically coupled to the electroactive element;

wherein the first and second electrodes are arranged such that the induced strain in the electroactive element causes a chirality of the vortex domain wall to change.

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30. The magnetic storage device of claim 29 wherein the magnetic wire is aligned along an axis extending between the first and second electrodes.

31. The magnetic storage device of claim 29 wherein the magnetic wire is curved.

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32. The magnetic storage device of any one of claims 29 to 31 comprising a magnetic tunnel junction structure coupled to the magnetic wire.

5 33. A method of operating a magnetic storage device according to claim 32, the method comprising:

applying a voltage between the first and second electrodes sufficient to generate a strain in the electroactive element that causes the domain wall in the magnetic wire to switch chirality; and

10 measuring the chirality of the vortex domain wall by measuring a resistance of the magnetic tunnel junction coupled to the magnetic wire.

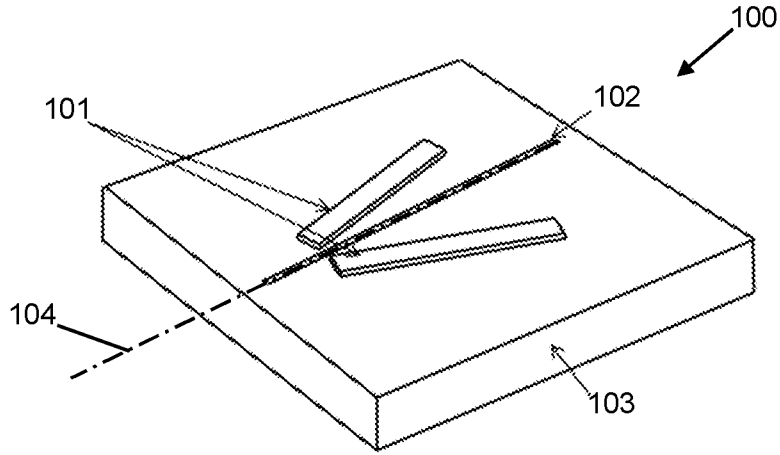


Fig. 1

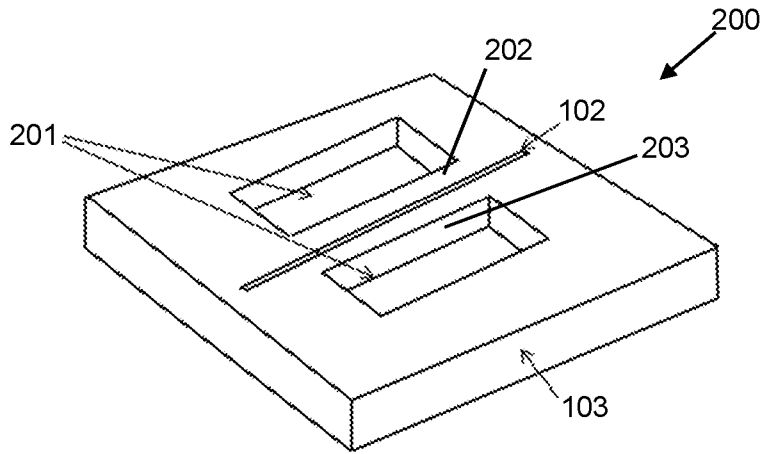


Fig. 2

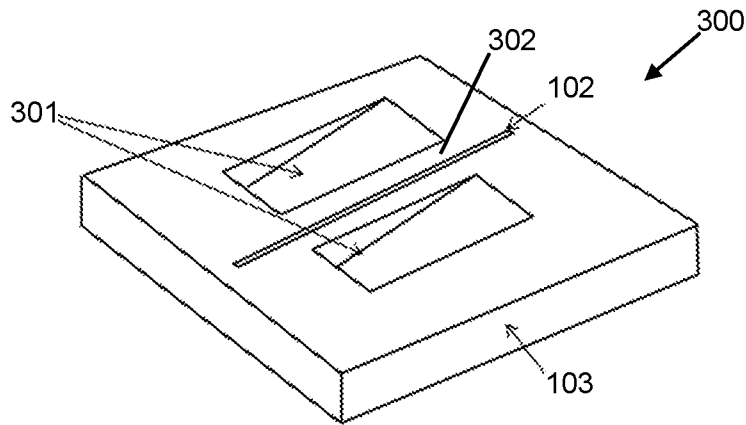


Fig. 3

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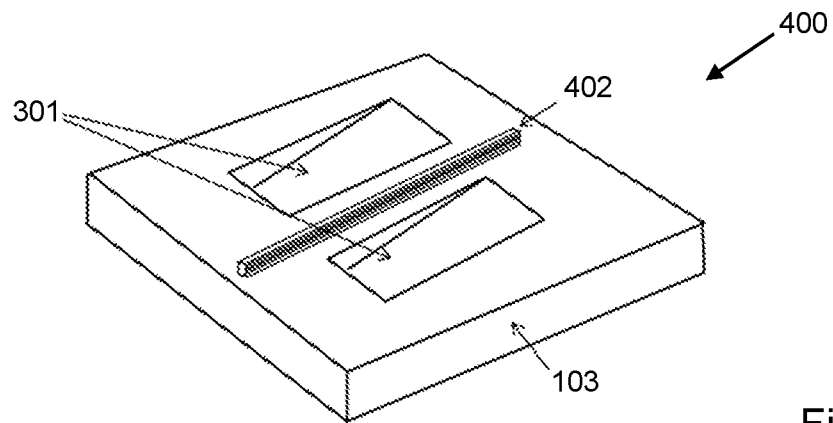


Fig. 4

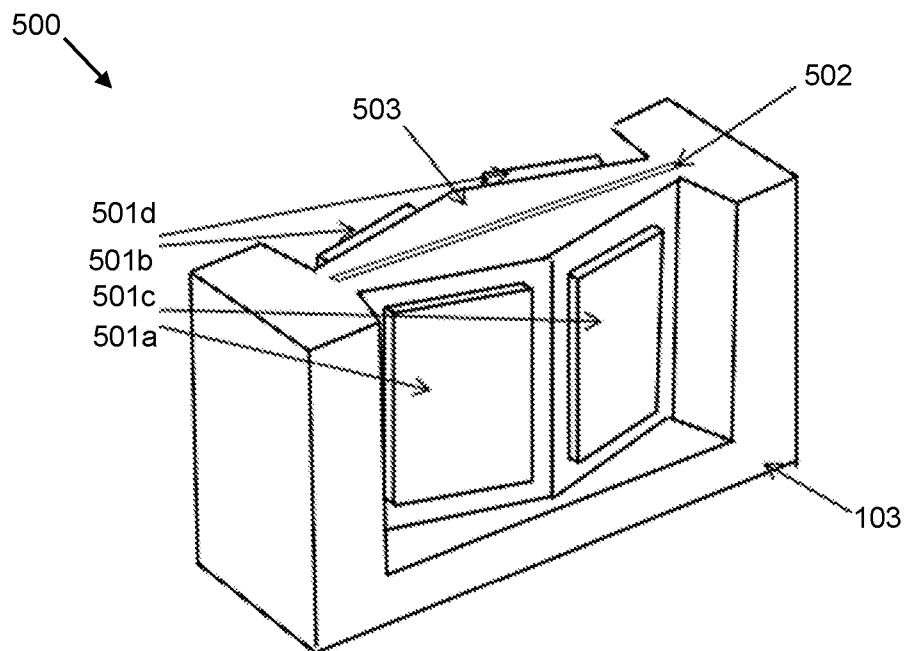


Fig. 5

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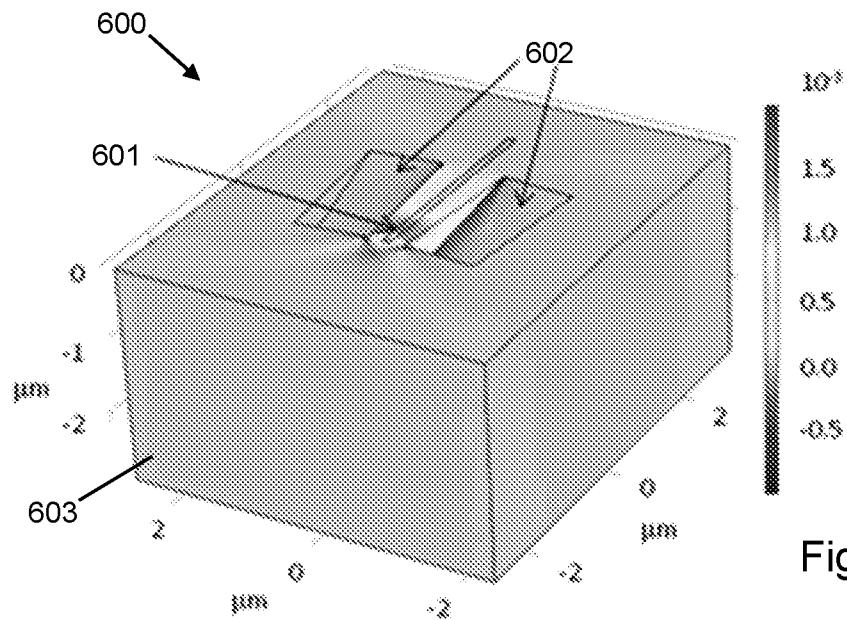


Fig. 6a

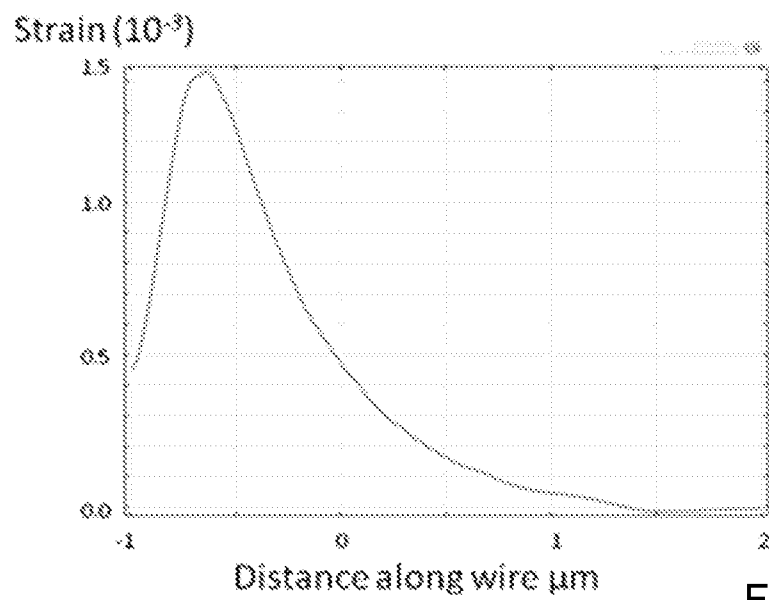
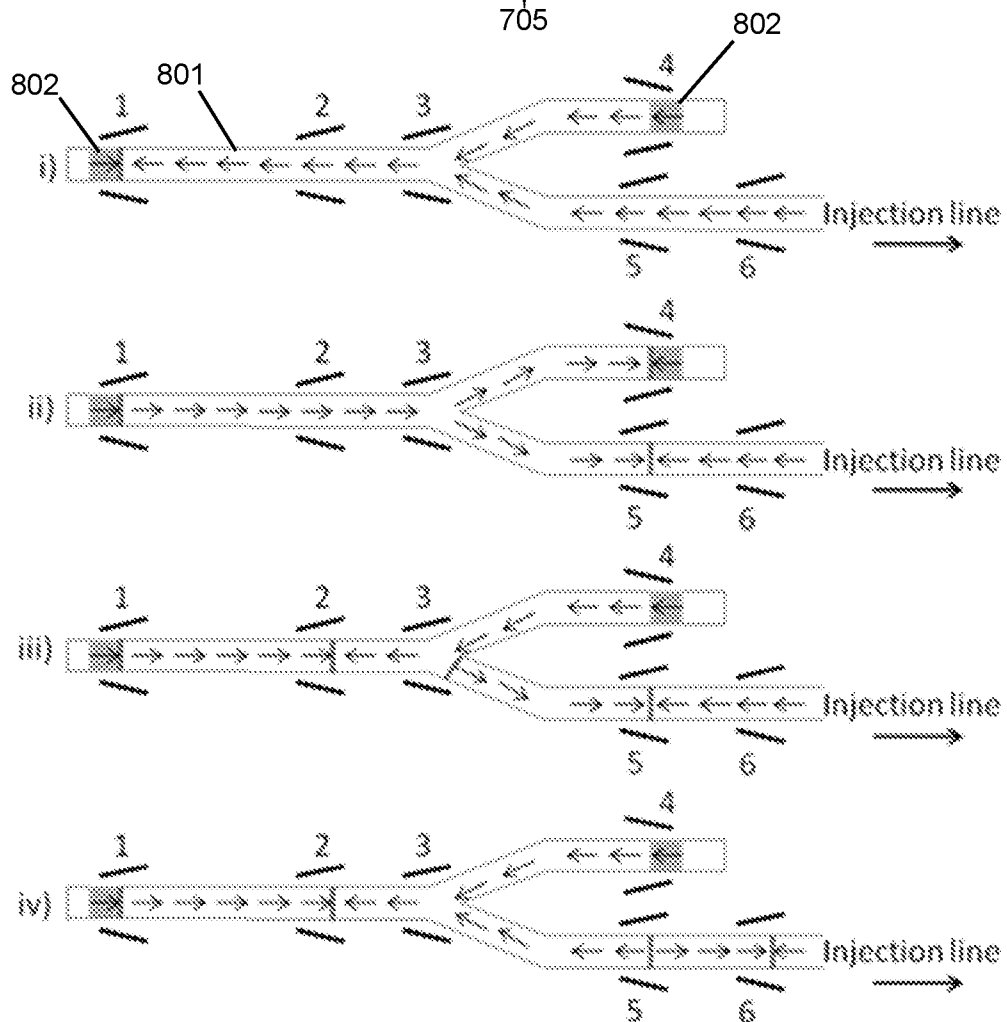
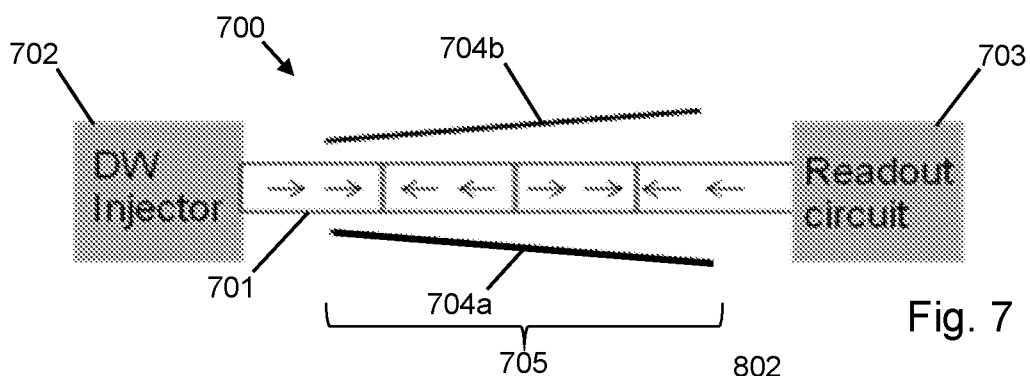


Fig. 6b



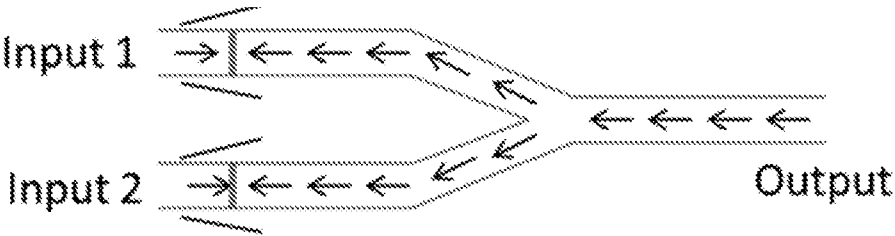


Fig. 9

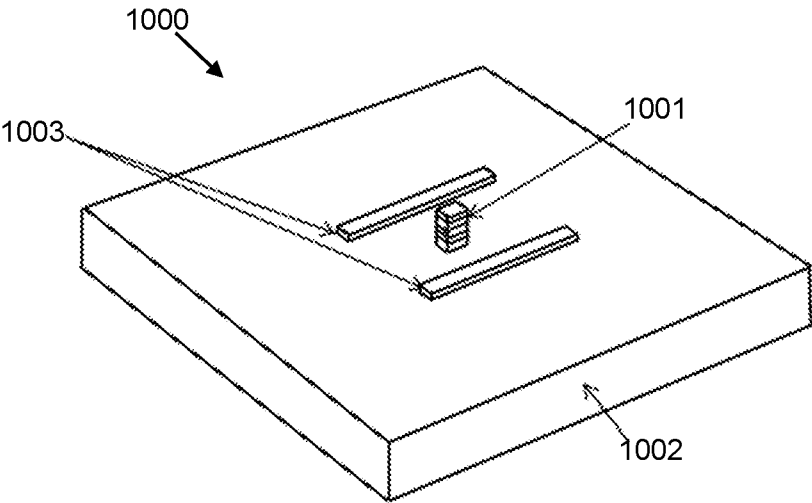
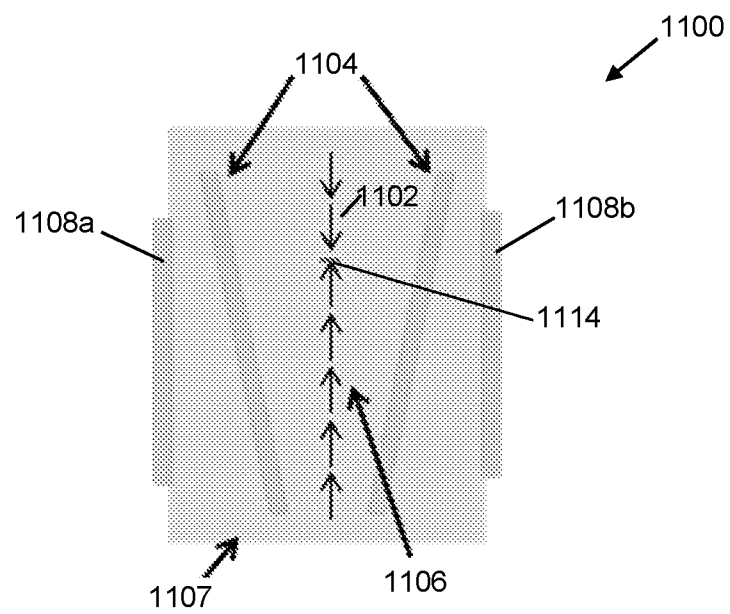
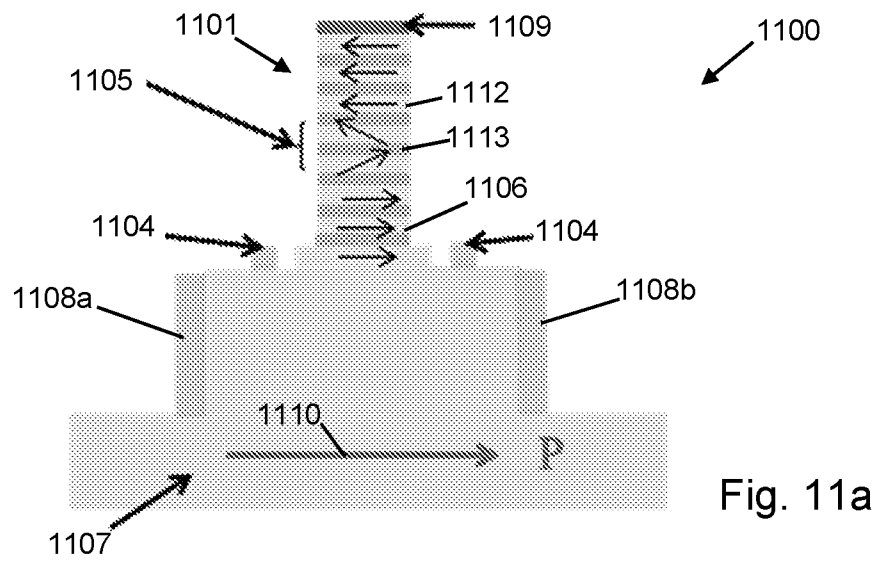


Fig. 10

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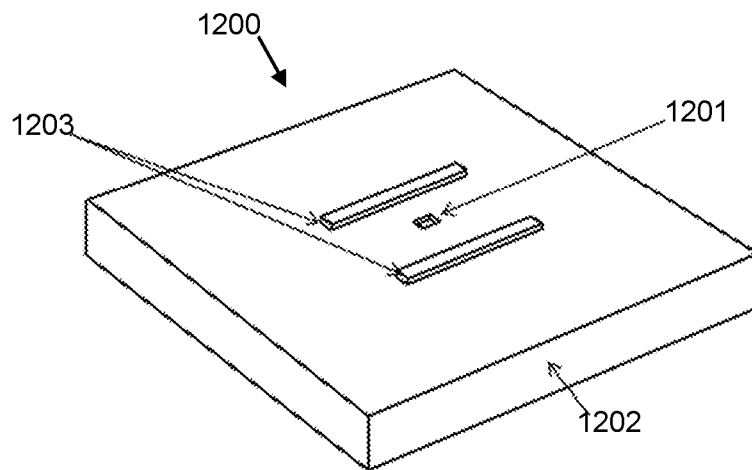


Fig. 12

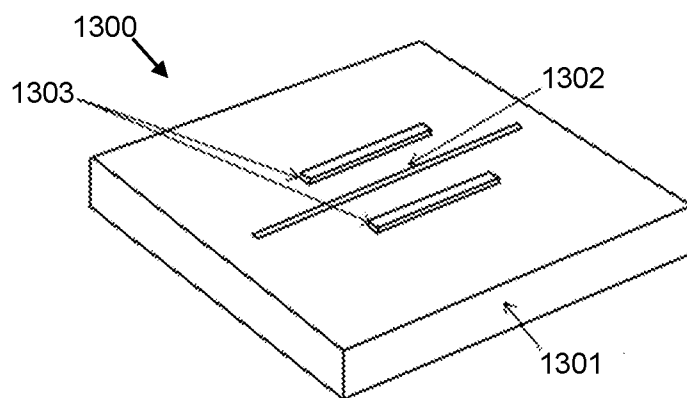


Fig. 13a

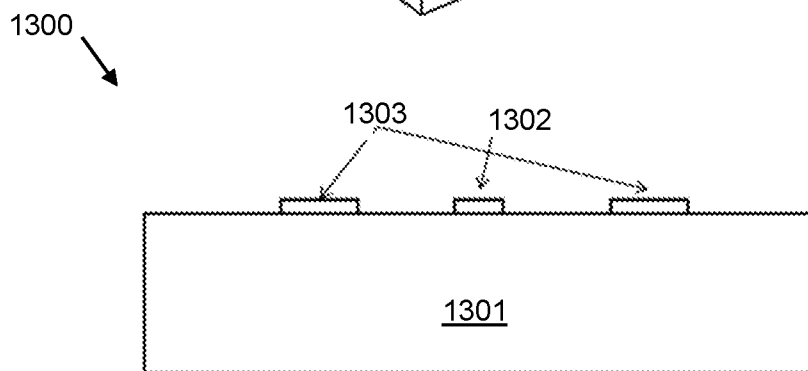


Fig. 13b

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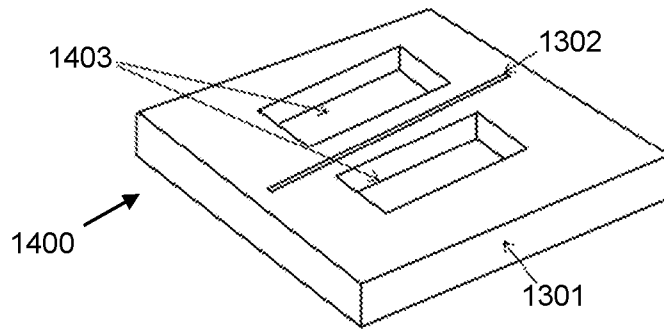


Fig. 14a

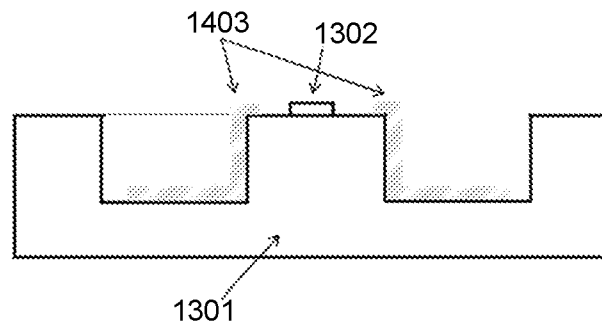


Fig. 14b

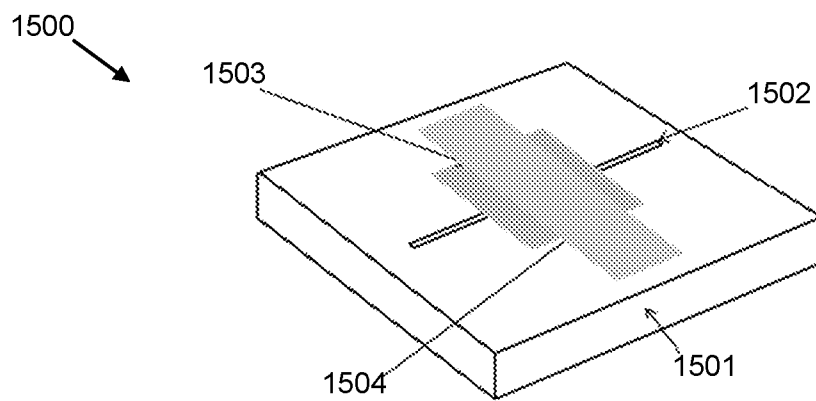


Fig. 15a

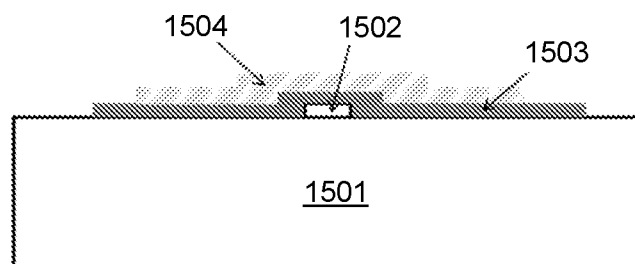


Fig. 15b

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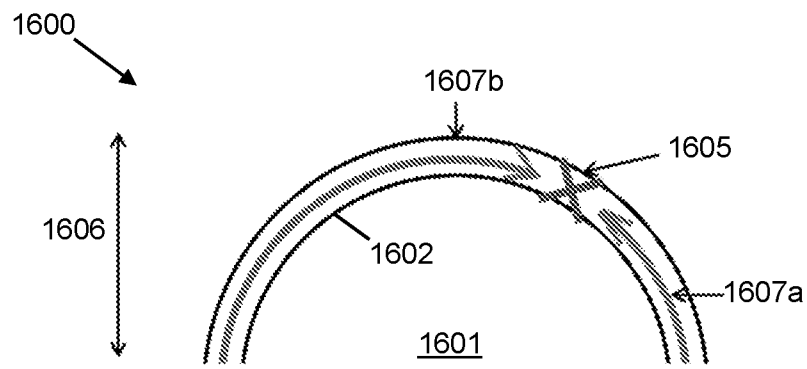


Fig. 16

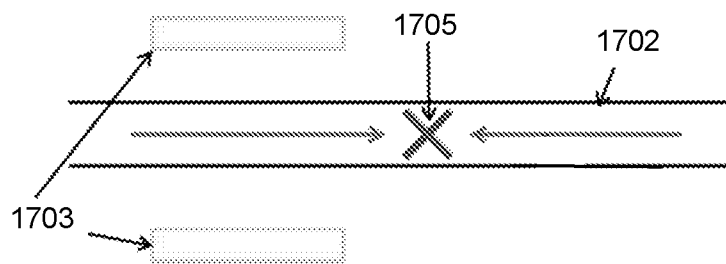


Fig. 17

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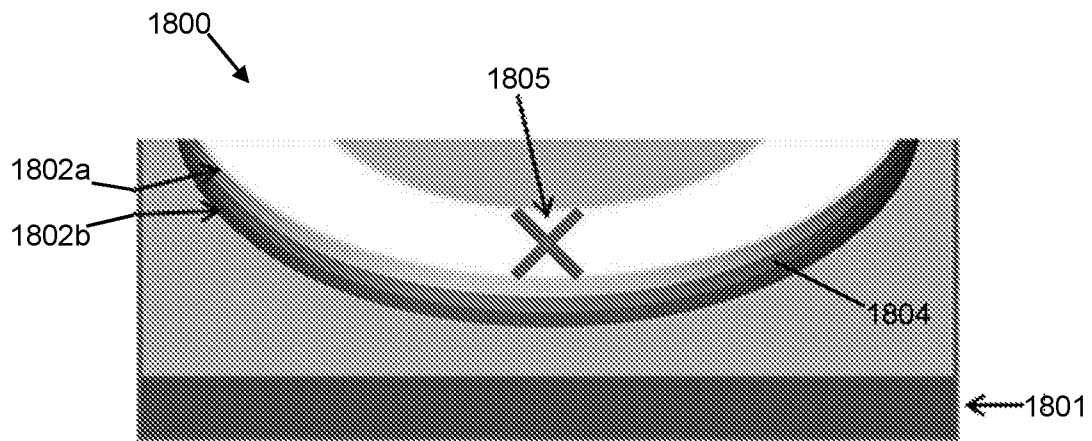


Fig. 18

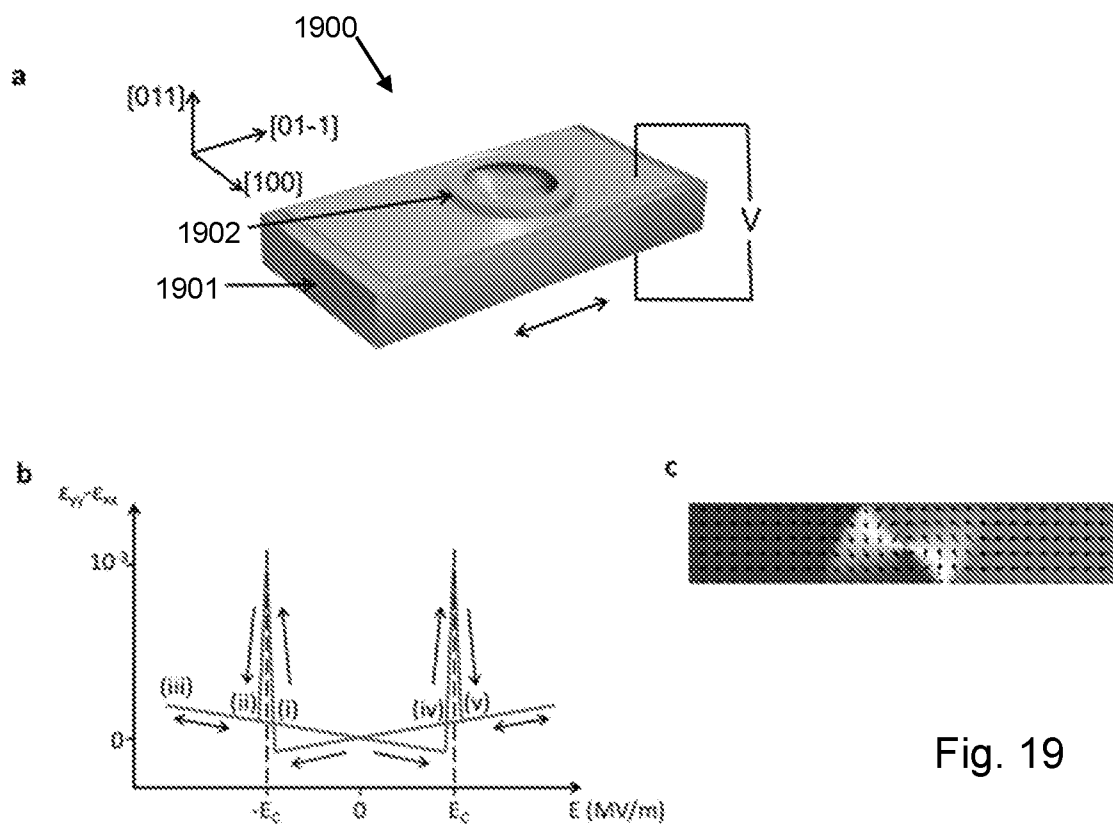


Fig. 19

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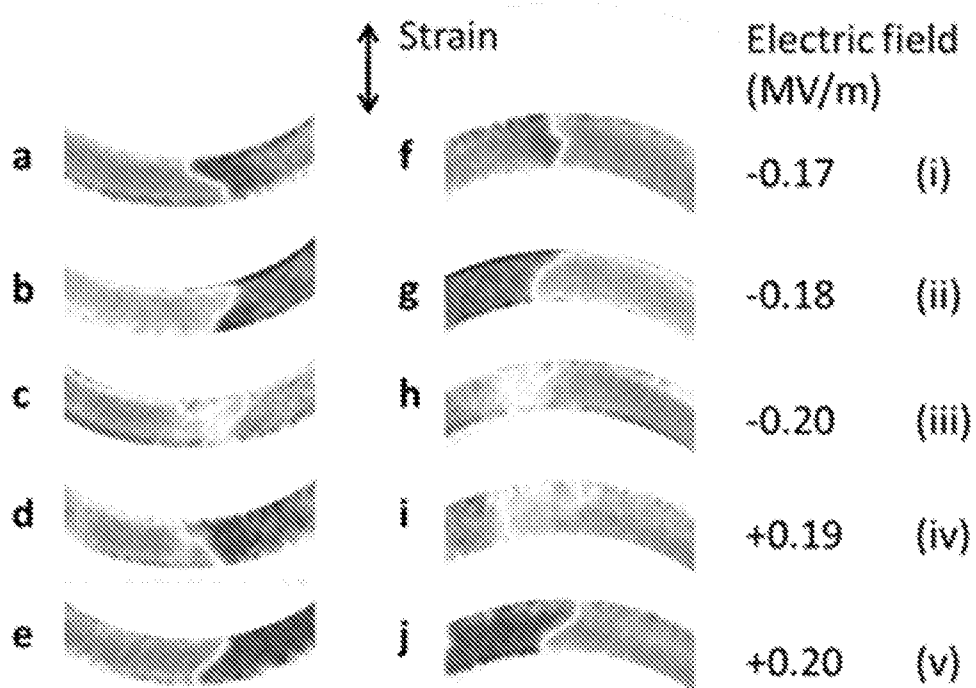


Fig. 20

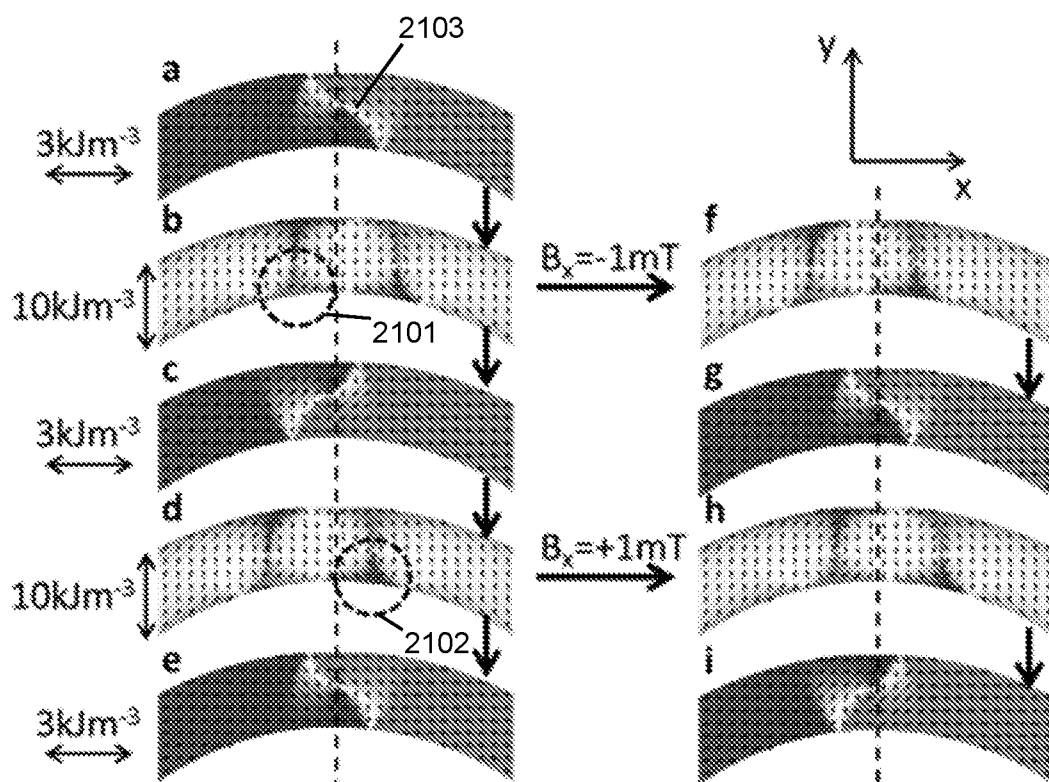


Fig. 21

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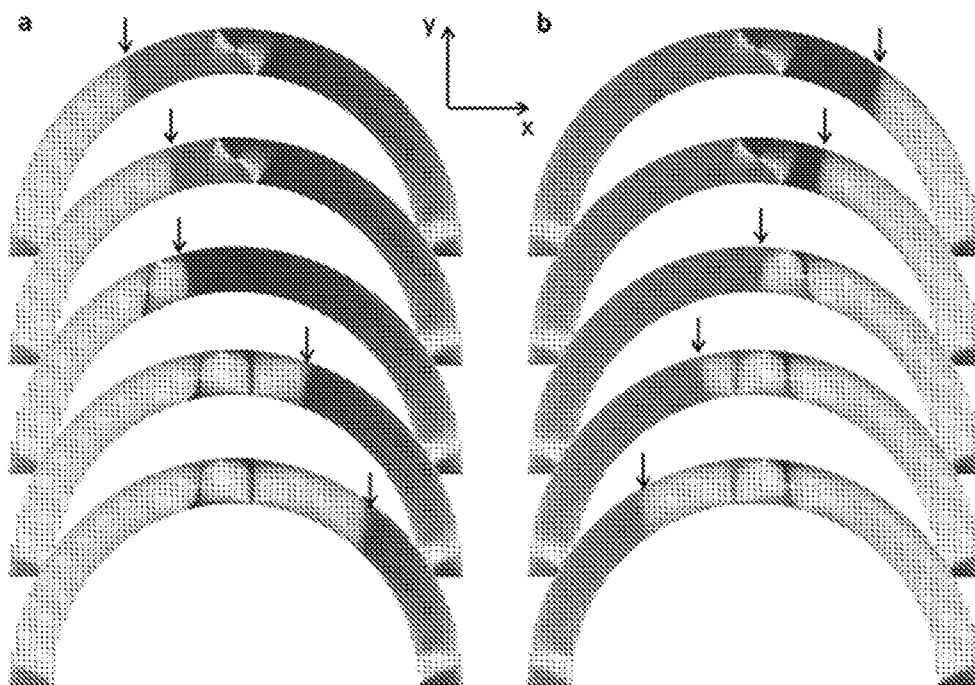


Fig. 22

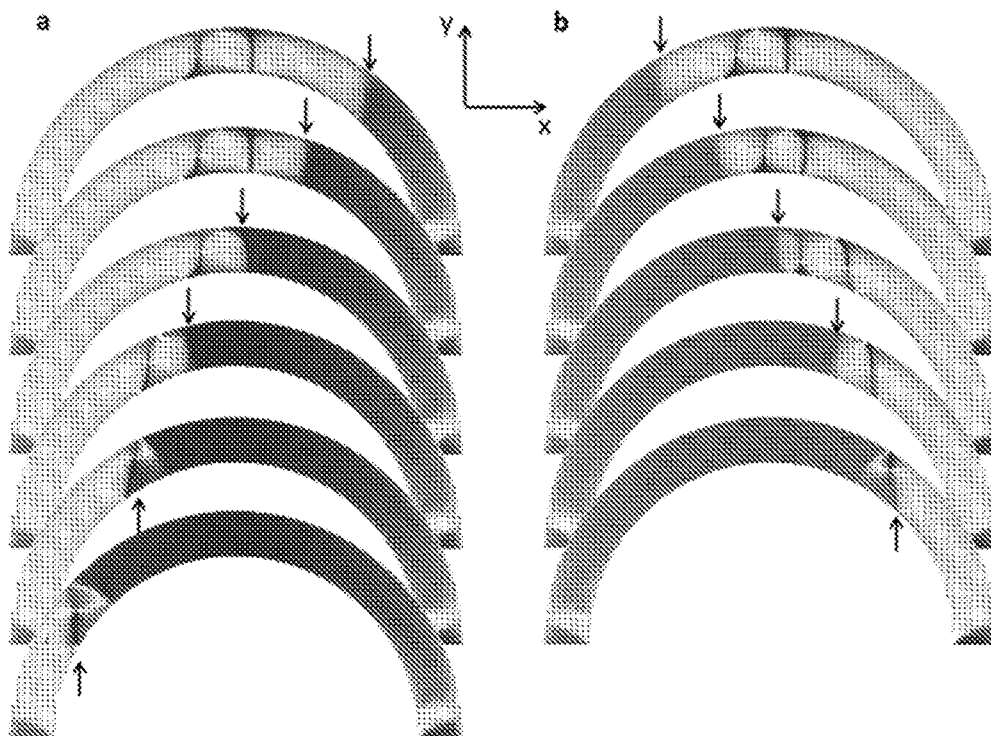
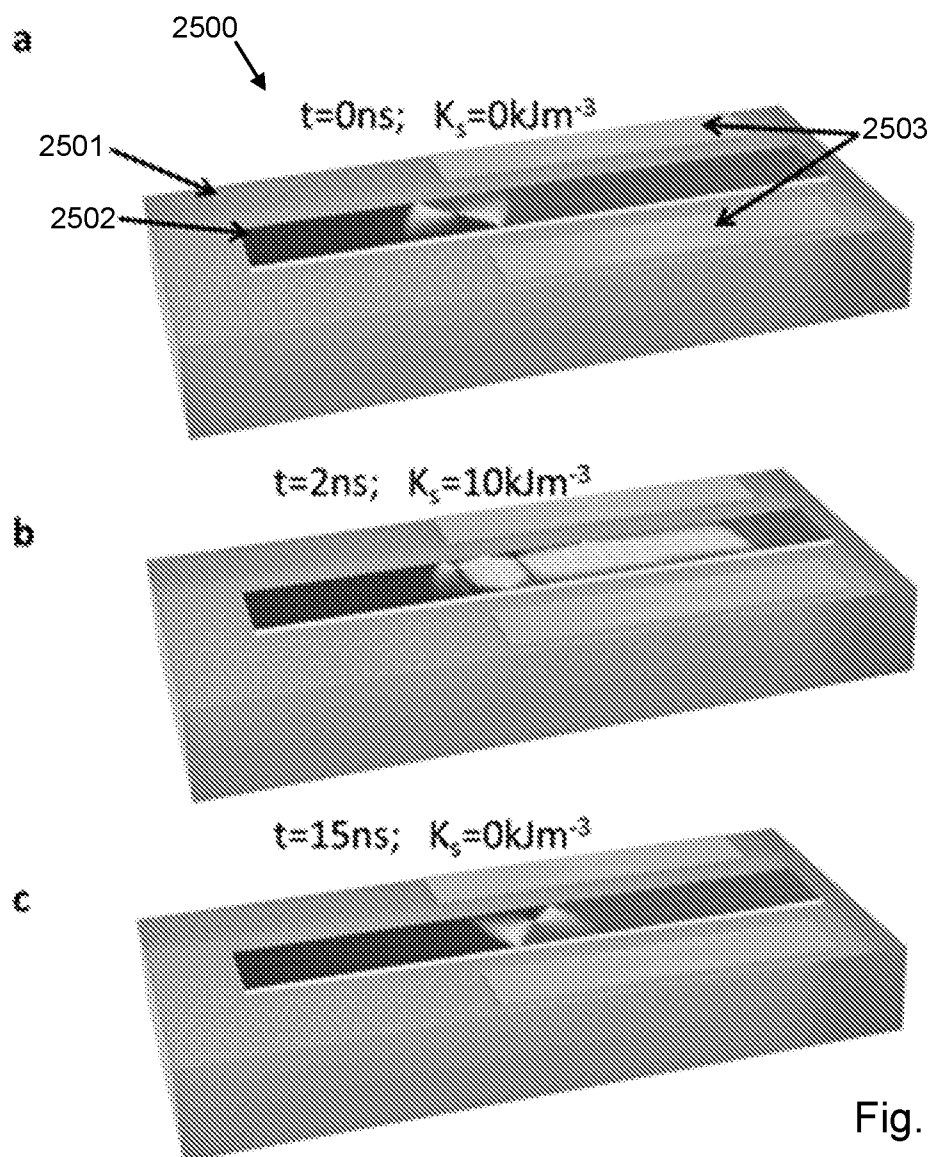
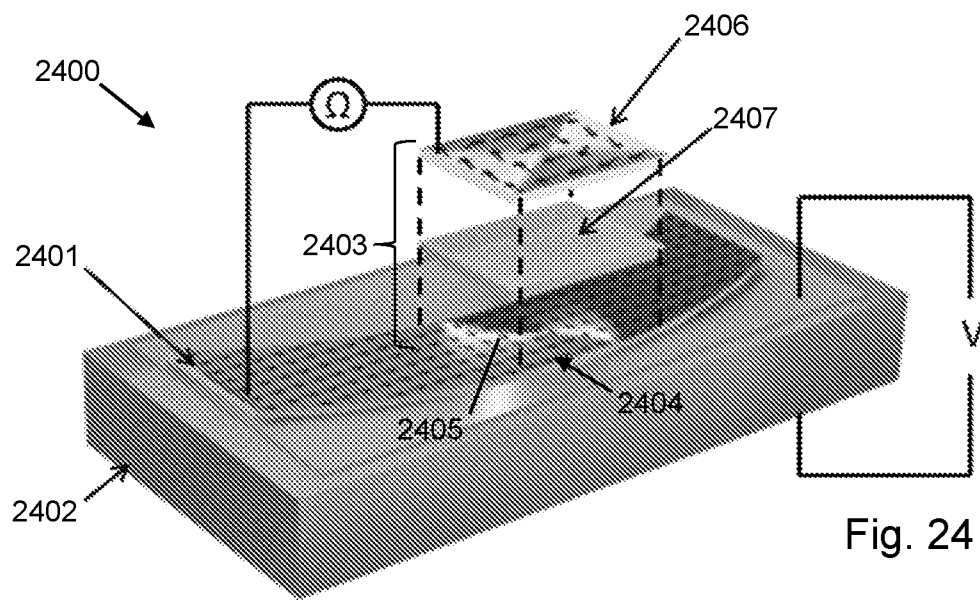


Fig. 23

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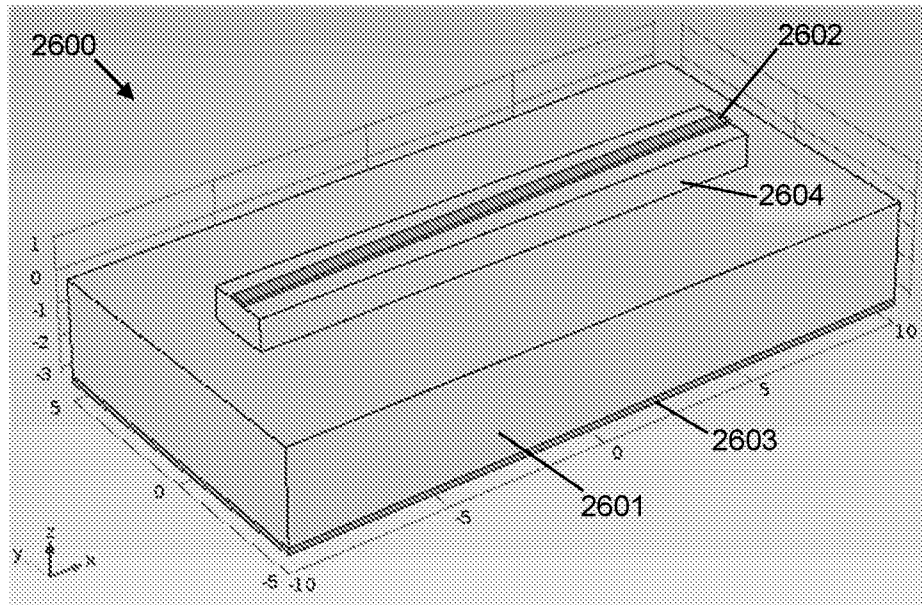


Fig. 26

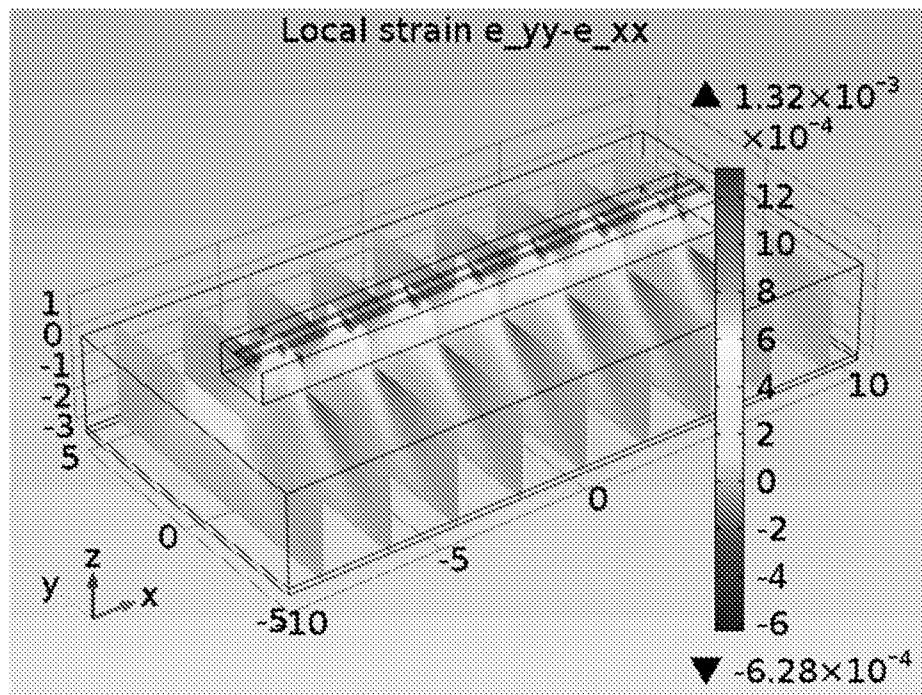


Fig. 27

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2016/051721

A. CLASSIFICATION OF SUBJECT MATTER
INV. G11C19/08 G11C11/16
ADD.

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)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2013/250668 A1 (FUKUZAWA HIDEAKI [JP] ET AL) 26 September 2013 (2013-09-26) paragraphs [0041], [0062], [0115]; figures 2-4,10a	1-28
A	NA LEI ET AL: "Strain-controlled magnetic domain wall propagation in hybrid piezoelectric/ferromagnetic structures", NATURE COMMUNICATIONS, vol. 4, 22 January 2013 (2013-01-22), pages 1-7, XP055300354, United Kingdom ISSN: 2041-1723, DOI: 10.1038/ncomms2386 cited in the application page 6, left-hand column, last paragraph - right-hand column, paragraph 2; figures 1,6b -/-	1-28



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

8 September 2016

Date of mailing of the international search report

08/11/2016

Name and mailing address of the ISA/

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Authorized officer

Colling, Pierre

INTERNATIONAL SEARCH REPORT

International application No

PCT/GB2016/051721

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	DEAN J ET AL: "Stress-based control of magnetic nanowire domain walls in artificial multiferroic systems", JOURNAL OF APPLIED PHYSICS, AMERICAN INSTITUTE OF PHYSICS, US, vol. 109, no. 2, 24 January 2011 (2011-01-24), pages 23915-1-23915-5, XP012147375, ISSN: 0021-8979, DOI: 10.1063/1.3532041 cited in the application page 3, left-hand column, paragraph 2 - page 4, right-hand column, paragraph 2; figures 3,4 -----	1-28
A	US 2012/250398 A1 (MORISE HIROFUMI [JP] ET AL) 4 October 2012 (2012-10-04) paragraph [0105] - paragraph [0118]; figures 22-26 -----	1-28
A	US 2013/163313 A1 (TIERCELIN NICOLAS [FR] ET AL) 27 June 2013 (2013-06-27) paragraph [0056] - paragraph [0133] -----	1-28

INTERNATIONAL SEARCH REPORT

International application No.
PCT/GB2016/051721

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

1-28

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 1-28

Magnetostrictive memory with domain wall movement controlled by application of voltage induced strain gradient to magnetic wire/stack

2. claims: 29-33

Magnetostrictive memory with strain induced vortex domain wall switching/transformation in magnetic wire

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2016/051721

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2013250668 A1	26-09-2013	JP 5653379 B2	14-01-2015
		JP 2013201174 A	03-10-2013
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US 2012250398 A1	04-10-2012	JP 5431400 B2	05-03-2014
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