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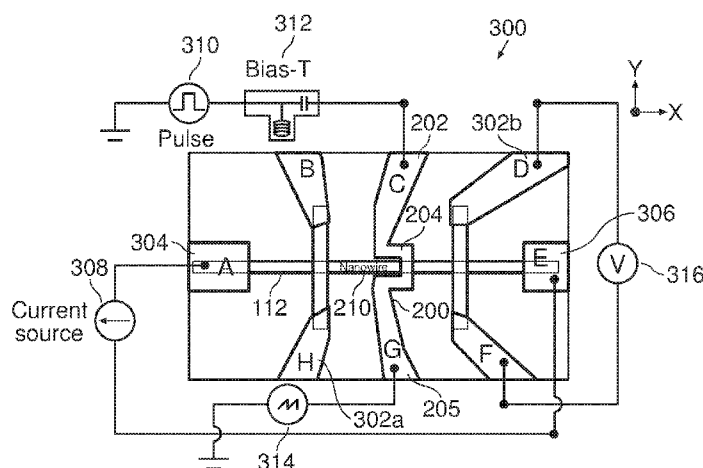


FIG. 3

(57) **Abstract:** A magnetic memory device (300) comprises a memory component (112) comprising perpendicular magnetic anisotropy material. The writing component comprises electrically-conductive material, the writing component being for writing a magnetic data bit in the PMA material, the writing component comprising a first segment (102, 202) and a second segment (104, 204), the first segment and the second segment meeting at an edge section (114, 214), the edge section being disposed facing the PMA material. The magnetic memory device injects an electrical pulse into the writing component for the generation of a localized magnetic field component (120, 220) from the edge section. In operation, this may write the magnetic data bit in the PMA material by inducing nucleation and/or a magnetic domain therein. Methods of operation are also disclosed.

MAGNETIC MEMORY DEVICES AND METHODS OF OPERATING THE SAME

The invention relates to magnetic memory devices. The invention also relates to methods of operation of magnetic memory devices. The invention has particular
5 application for the writing of a magnetic memory bit in a memory component such as a nanowire comprising Perpendicular Magnetic Anisotropy (PMA) material.

Magnetic data storage devices such as domain wall (DW) memory and Magnetic
Random Access Memory (MRAM) devices have been dubbed as amongst the most
10 promising candidates that can fulfil the role of a universal memory [1-3]. In such devices, the data bits "1" and "0" are represented by magnetic domains oriented in one of the two possible directions. To write a magnetic data bit, an electrical current is pulsed through a magnetic writing component, also known as an injection line. These injection lines typically comprise a (relatively) thick and conductive nanowire
15 deposited on top of a memory data line, which is the memory component being used to store the data bits. This data line is also typically a nanowire. An electrical pulse is generated and applied to the injection line which, in turn, causes a magnetic field to be induced in the area surrounding the injection line typically in the form of an Oersted field which causes the magnetic data bits to be written in the data line
20 disposed within the generated Oersted field. The direction of the applied electrical pulse (or, rather, the current) can be reversed, with different current directions used to write either "1" or "0" bits [4-6].

Magnetic memory devices were first demonstrated in in-plane materials. However,
25 the first domain wall memory demonstrated in in-plane magnetic anisotropy (IMA) material has very large DW widths of about 100 ~ 200 nm which limits its scalability [4, 5]. In addition, the current-driven domain wall dynamics is very sensitive to external magnetic fields and suffers from a high intrinsic pinning [6-11].

Domain Wall memory design has been moving towards the use of high PMA materials. This type of magnetic memory has a small domain size, narrower domain walls, much higher domain wall thermal stability and a much higher pinning field than that of in-plane magnetized systems any or all of which may be advantageous for the thermal stability of the device [7-10]. The current-induced domain wall motion in such systems is dominated by the field-insensitive adiabatic torque which moves the domain wall by changing its structure between Bloch and Neel walls periodically [8, 9, 11, 16, 17]. Therefore, the threshold current density required for domain wall propagation is given by the energy difference between the two types of domain walls. As compared to an IMA system, the threshold current density for DW motion in a PMA system is lower [18–21].

For the realization of domain wall-based memory devices, it is important to first optimize the injection of a domain wall into the nanowire. In the known technique mentioned above, domain wall injection is achieved by applying an electrical current via a thick and conductive strip line deposited on top of the magnetic nanowire. The Oersted field generated by the conductive strip line is used to change the magnetization direction of the magnetic nanowire, with the magnetization direction depending on the direction of the current applied [4-6, 10]. To create domain walls in PMA materials, the minimum amount of magnetic energy required from the injection line is approximated by the product KV , where K is the effective magnetic anisotropy energy and V is the volume of the magnetic domain [12]. While high K materials favour the thermal stability of a PMA device, the emerging problem is that it would then require increasing amounts of energy to perform magnetic bit writing. For the known method, the current density required to nucleate a domain wall is approximately $\sim 10^{12}$ A/m² [4-6, 8-12, 16-17, 22-23]. Reducing the energy consumption by improving the injection line design is therefore seen as an important consideration.

The invention is defined in the independent claims. Some optional features of the invention are defined in the dependent claims.

Implementation of the techniques disclosed herein may offer significant technical advantages. For instance, novel arrangements for the magnetic writing component/injection line for efficiently injecting data bits into PMA magnetic memory devices are disclosed. As disclosed herein, there are novel arrangements for magnetic writing components, which may comprise an injection line such as a micro-coil which has been patterned using, for instance, standard electron beam lithography and/or magnetron sputtering fabrication processes. Under an applied electric potential, the geometry of the writing component, described below, may generate a highly shaped and focused electric current. This current can produce a high magnitude and localised magnetic field that can easily initiate the nucleation of a magnetic domain in a memory component (such as a nanowire) disposed within the magnetic field. Use of the techniques disclosed herein may mean that the magnetic data bit can be deterministically written bit using only an 8 ns pulse with a current density of, say, $4.97 \times 10^{11} \text{ A/m}^2$ or a 15 ns pulse with a current density of, say, $5.35 \times 10^{11} \text{ A/m}^2$. As a result, the disclosed methods consume less than 30%, perhaps around 28%, of the energy required by known injection designs, such as that disclosed in [23].

As described herein, highly angular shaped injection line designs are proposed. It may be that a domain wall can be deterministically injected with current amplitudes as mentioned in the preceding paragraph. Both experimental and simulation results show that the techniques disclosed herein consume about 30% of the energy required by known injection designs.

As disclosed herein, an improved memory writing component for more efficient magnetic data bit writing is provided. The memory writing component – for instance,

an injection line – has a design that can focus and shape the current density distribution to reduce the threshold current needed to write a magnetic data bit.

As such, the novel arrangements disclosed here obviate any issues which might arise
5 from magnetic data bit writing in such high PMA materials consuming increasing amounts of energy. Significantly reduced amounts of energy are required by implementing the techniques disclosed herein.

The invention will now be described, by way of example only, and with reference to
10 the accompanying figures in which:

Figure 1 is a series of schematic representations of memory writing components in accordance with the techniques disclosed herein;
Figure 2 is a schematic representation of another memory writing component in
15 accordance with the techniques disclosed herein;
Figure 3 is a schematic representation of a magnetic memory device incorporating a memory writing component according to the principles of the memory writing component of Figure 2;
Figure 4 is a series of graphs illustrating properties of a memory component as may
20 be used in the magnetic memory device of Figure 3;
Figure 5 is a series of diagrams illustrating domain wall propagation;
Figure 6 is a series of polar Kerr images of a PMA nanowire after domain injection while sweeping a small magnetic field, normalised Hall resistance measurement of the nanowire after the injection and schematic illustrations of the magnetisation;
25 Figure 7 is a series of curves illustrating domain injection probability in respect of differing properties in the memory writing component;
Figure 8 is a series of views providing a comparison of current density distribution, magnetic field and time-resolved magnetisation between the known technique mentioned above and the innovative techniques disclosed herein;

Figure 9 is a series of curves illustrating magnetic bit writing performance of the techniques disclosed herein in comparison with a known technique;

Figure 10 is a series of representations illustrating the current density distribution and Z-axis magnetic field resulting from variation of the properties of the magnetic

5 writing component according to the techniques disclosed herein;

Figure 11 provides an illustrative comparison of one application of the techniques disclosed herein in a magnetic tunnel junction (MTJ) device and a known technique;

Figure 12 is a schematic representation of a known three-terminal MTJ device; and

Figure 13 is a more detailed schematic representation of an application of the
10 techniques disclosed herein in a MTJ device.

Turning first to Figure 1(a), a first writing component for use in a magnetic memory device is illustrated. Writing component 100 comprises a first segment 102 and a second segment 104 and, as best viewed in Figure 1(b), the writing component 100
15 has a thickness 105.

In the example of Figure 1(a), writing component 100 is formed of electrically-conductive material and arranged generally in the shape of the Greek character Λ (lambda), or to give it an alternative expression, it can be considered to be arranged
20 in an inverted V-shape, with the first segment 102 and second segment 104 extending away from an apex 106, which comprises a straight or generally straight edge running along the thickness 105 of the writing component 100. The first and second segments 102, 104 extend away from apex 106 at an angle. As best viewed in Figure 1(c), the first segment 102 and the second segment 104 meet (or merge into
25 one another) at a boundary section 108 between the two segments.

Because the first and second segments 102, 104 extend away from each other at the edge section 116 (or the apex 106) an angle, an area or volume 110 is formed between the segments 102, 104, with the segments 102, 104 defining, at least in
30 part, this area/volume 110. In this example, a memory component 112 (viewed in

section in this figure), or at least a part thereof, is disposed in this area/volume 110 between the first and second segments 102, 104. In the example of Figure 1, the memory component 112 can take a number of forms, including a cylindrical (or generally cylindrical) magnetic structure, or a cuboidal (or generally cuboidal) magnetic nanowire. In this example, the memory component 112 is illustrated being spaced from the first and second segments 102, 104 of the writing component 100, but in alternative arrangements, the memory component 112 may be in contact with one or both of these segments 102, 104.

Writing component 100 is manufactured such that the transition between the first segment 102 and the second segment 104 at the boundary section 108 results in generally straight and sharp edges: the apex 106 and an opposed edge 114 which also runs along the thickness 105 of the writing component 100 as perhaps best viewed in Figure 1(b). In this respect, a “sharp” edge is formed when the edges of the two segments which meet define straight or substantially straight lines, akin to, say, an edge of a cuboid. In this respect, the edge 114 can be considered an “interior” edge, given the fact it is facing memory component 112 and, consequently, apex 106 may be considered an “exterior” edge. That is, the edge section 116 comprises a sharp edge 114 defining a boundary between the first segment 202 and the second segment 204 of the writing component 100.

As will be described in further detail below, writing component 100 may be subjected to an electrical pulse. Because of the geometric shape of the writing component 100, particularly because of the edge 114, the current distribution in the writing component 100 is concentrated at an edge section 116 (illustrated schematically only in Figure 1(a)) proximal to the edge 114. As best viewed in Figure 1(b), a part 118 of the surface of the writing component 100 at the edge section 116 is disposed facing towards the memory component 112. A localised magnetic field component represented by arrow 120 is generated by the concentrated current distribution in edge section 114 and emanating from or near surface portion 118.

This magnetic field component may initiate nucleation of a magnetic domain in the memory component 112, causing the writing of a magnetic data bit therein.

In the arrangement of Figures 1(a) and (b), the “interior” edge 114 is a sharp edge, as explained above. In the alternative arrangement of Figure 1(c), the edge 114 is a rounded edge having a radius. The radius may be constant or variable across the arc of the curve of the rounded edge. That is, the edge section 116 may comprise a rounded edge 118 were the first segment 102 and the second segment 104 of the writing component 100 meet.

Although this is discussed in more detail with reference to Figure 10, it is sufficient to say for the moment that it has been found that a satisfactory concentrated current distribution can be achieved in the edge section 116, even with a rounded edge (which may result from the practical limitations of manufacturing techniques, particularly when working in very small dimensions), with the concentrated current distribution being sufficient to generate a magnetic field component 120 to induce nucleation of a domain wall in memory component 112.

In one arrangement, the first and second segments are formed integrally. In one arrangement, the first and second segments are connected at an angle of between 1 and 150 degrees, preferably at an angle of between 20 and 130 degrees, more preferably at an angle of between 40 and 120 degrees, yet more preferably at an angle of between 60 and 110 degrees, and yet more preferably at an angle of between 80 and 100 degrees.

Figure 2 illustrates a further alternative arrangement, where the writing component 200 is not provided in a Λ /inverted-V shaped. In this arrangement, the writing component 200 is formed generally to resemble the Greek character Π (Pi), or, considered alternatively, generally in the form of an n-shape. Thus, writing component 200 in this example comprises three main segments: first segment 202,

second segment 204 and third segment 205. In this example, first segment 202 and second segment 204 adjoin one another, and are formed at right angles to one another; that is, the first segment 202 and the second segment 204 each extend away from the apex (or corner) 206a at 90 degrees from one another. Similarly,
5 second segment 204 and third segment 205 are formed at right angles to one another, extending at 90 degrees from one another from apex/corner 206b.

Similarly, the first and second segments 202, 204 form an area/volume 210, this time in conjunction with third segment 205 in which at least a part of memory
10 component/nanowire 112 is disposed.

In a similar fashion as to the arrangements of Figure 1, edges 214 are formed where, respectively, the first segment 202 meets (in this case merges into) the second segment 204, and where the second segment 204 meets (merges into) the third
15 segment 205. Again, edge sections are defined in the areas represented schematically by 216. Surface portions 218 of edge sections 216 are disposed facing towards the memory component 112. Because of the sharp edge geometry at the edges 114, when the writing component 200 is energised, the current distribution in the edge sections 216 are again concentrated, thereby generating magnetic field
20 components (represented by the arrows 220) which may induce nucleation of a domain wall in memory component 112.

Thus in the example of Figure 2, the injection line has a Π -shaped or n-shaped portion. The Π -shaped or n-shaped portion may include a first segment 202, a
25 second segment 204 and a third segment 205. The first segment 202 and the third segment 205 may be disposed at or near two opposite ends of the second segment 204. The first segment 202 and the third segment 205 may be parallel or generally parallel to each other. The first segment 202 and the third segment 205 may extend perpendicularly from the second segment 204. The first segment 202 and the third
30 segment 205 may extend perpendicularly from two opposite ends of the second

segment 204. The first segment 202, the second segment 204 and the third segment 205 may be formed integrally using, for example, one of the techniques mentioned above.

- 5 Or, to put it another way, the writing component 200 comprises a third segment 205, the first segment 202 and the third segment 205 extending generally perpendicularly from the second segment 204, thereby forming a volume 210 defined in part by the first segment 202, the second segment 204 and the third segment 205 in which a portion of the memory component 112 is disposed.

10

The angle between the first segment 202 and the second segment 204 may range between 70 and 100 degrees, preferably between 80 and 95 degrees. Similarly, the angle between the second segment 204 and the third segment 205 may also range between 70 and 100 degrees, preferably between 80 and 95 degrees. As illustrated
15 in Figure 2, the edges 214 may be a sharp edge. However, it will be appreciated that these edges may be a rounded edge, in a similar fashion to the arrangement of Figure 1(c). It may be preferred that the radius of the rounded edge has a radius of up to a width of the second segment 204.

- 20 It will be appreciated that a highly angular injection line design such as the designs illustrated in Figures 1 and 2 is proposed – whether using sharp or rounded edges – which can electrically inject magnetic domains and/or domain walls efficiently into the memory component/nanowire.

- 25 For certain memory types, the domain wall(s) may be used for magnetic storage. For other memory types, the domain(s) may be used for magnetic storage.

Figure 3 is a schematic representation of a magnetic memory device incorporating a magnetic memory writing component. While Figure 2 is given in the context of a
30 memory writing component according to the principles of Figure 2, it will be

appreciated that additionally or alternatively, one of the writing components illustrated in Figure 1 may also be used.

In summary, Figure 3 illustrates a magnetic memory device 300 having a writing component 200 having first, second and third segments 202, 204, 205. Thus, the figure illustrates the scanning electron microscopy image of a Π -shaped device, including the proposed writing component/injection line 200 with terminals C-G, two Hall bars 302a, 302b having, respectively, terminals B-H and D-F. Also illustrated, is the memory component 112, in this instance a PMA nanowire fabricated horizontally across, having electrical terminals A-E 304, 306 acting as a current source and sink across which a Hall Effect bias current may be applied using current source 308. In this example, one or more of the writing component/injection line and the other electrical connects may be fabricated using, for example, tantalum (Ta) (e.g. 6.3 nm)/copper Cu (93.6 nm)/gold Au (24 nm). Other materials may also be used, including but not limited to gold (Au), aluminium (Al), tungsten (W), titanium (Ti), chromium (Cr), and ruthenium (Ru) can be used for fabricating the injection line and/or one or more of the electrical connects. In addition, the dimensions of the materials can differ according to the materials used or according to the desired dimensions.

20

In one arrangement, the resistivity R_H of the Hall bars is used to detect the magnetization of the nanowire underneath by exploiting the Anomalous Hall Effect. The Hall resistivity is empirically fitted by the formula [24]:

$$\rho_H = R_0 B + 4\pi R_s M \quad (1)$$

25

where B is the applied magnetic field, M is the magnetization per unit volume. R_0 and R_s are the ordinary and the anomalous Hall coefficient, respectively. In the example of Figure 3, R_s may be substantially larger than R_0 . In such cases, the R_{Hall} is proportional to the perpendicular component of the local magnetization of the nanowire beneath the Hall bar.

30

Thus it will be appreciated that Figure 3 illustrates a magnetic memory device 300 comprising: a memory component 112 comprising perpendicular magnetic anisotropy, PMA, material; a writing component 200 comprising electrically-
5 conductive material, the writing component being for writing a magnetic data bit in the PMA material, the writing component comprising a first segment 202 and a second segment 204, the first segment and the second segment meeting at an edge section 216, the edge section 216 being disposed facing the PMA material (in the magnetic component/nanowire 112); and wherein the magnetic memory device 300
10 is configured to inject an electrical pulse into the writing component 200 for the generation of a localised magnetic field component 220 from the edge section 216.

It will also be appreciated that a method of writing a magnetic data bit in a magnetic memory device 300 is illustrated. This magnetic memory device 300 comprises a
15 memory component 112 comprising perpendicular magnetic anisotropy, PMA, material; and a writing component 200 comprising electrically-conductive material, the writing component 200 comprising a first segment 202 and a second segment 204, the first segment 202 and the second segment 204 meeting at an edge section 216, the edge section 216 being disposed facing the PMA material (in the magnetic
20 component/nanowire 112), the method comprising injecting an electrical pulse into the writing component 200 to generate a localised magnetic field component 220 from the edge section 216.

It will be appreciated that references in the preceding two paragraphs to the edge
25 section 216 formed between the first and second segments 202, 204 may also be substituted by references to the edge section 216 formed between the second and third segments 204, 205. It will also be appreciated that references to the writing component 200 may be substituted by references to the writing component 100, and parts thereof, of Figure 1.

30

- To inject a domain into the memory component/magnetic nanowire, a potential pulse of duration t_p from pulse generator 310 is applied through the bias-T 312 across the injection line on terminals C-G. Circuit parameters may be observed using one or more of oscilloscope 314 and voltmeter 316. Figures 4(a)-(d) show the
- 5 measured resistivity R_H as a function of sweeping fields. Without an injected domain, the coercivity of the nanowire may be 190 Oe or thereabouts, as shown in Figures 4(a) and (b). With a successful domain injection, the magnetization of the nanowire may be found to switch at a much lower field of 50 Oe, as shown in Figures 4(c) and (d). Domain walls are topological defects in the magnetization which can propagate
- 10 swiftly across the nanowire, causing a magnetization reversal even before the coercive field for a uniformly magnetized nanowire is reached. Subsequently, the domain injection probability for each pulse duration t_p and potential is illustrated from 20 repeated measurements.
- 15 Basically, Figures 4 (a) and (b) illustrate the Normalized Hall resistance of the PMA nanowire without domain injection, under a 2000 Oe and 370 Oe sweeping magnetic field and Figures 4 (c) and (d) illustrate the Normalized Hall resistance of a PMA nanowire with domain injected in the +z (-z) direction.
- 20 Figure 4(e) shows the typical R_{Hall} measurement while sweeping a 370 Oe external magnetic field in the z-direction, perpendicular to the nanowire. The square loop indicates that the nanowire exhibits a strong PMA. The y-axis of the graph is the normalized R_{Hall} , where 1 and 0 correspond to the complete alignment of the magnetization beneath the Hall bar in the + z and – z magnetization, respectively.
- 25 R_{Hall} was observed to change at 197 Oe, which corresponds to the magnetization reversal field. The sudden switch can be explained by the nanowire reversal process – a domain first nucleates at a defect in the nanowire and then, by means of domain wall motion, the domain rapidly expands throughout the nanowire until saturation results. As the threshold field for domain wall motion is less than the domain wall

nucleation field of the nanowire, only a single change in R_{Hall} was expected for each sweep direction.

In one exemplary setup, before domain wall injection, a perpendicular field of 370 Oe was applied to saturate the nanowire magnetization in the $-z$ direction. Domain wall injection may then be carried out by applying a current pulse to the injection line from C to G without an external magnetic field. The current pulse generates a local Oersted field with perpendicular field components at the sides of the injection line. If the amplitude and duration (t_p) of the pulse reaches the threshold value, a magnetic domain 500 will be introduced in the nanowire as shown in Figure 5(i) between the pair of domain walls 502. In the section 500, the magnetisation direction is up, and in the sections 504, the magnetisation direction is down. After the domain nucleation process, a magnetic field was swept as shown in Fig. 4(f). As the magnetic field increases from 0–370 Oe, R_{Hall} changes sharply from 0–1 at $H = 57$ Oe, which corresponds to the DW propagation field at which the DW is driven across the Hall bar. At 370 Oe, the magnetic nanowire is completely saturated (Fig. 5(ii) and (iii)) and R_{Hall} only switches at $H = 197$ Oe with the next field sweep.

As such, an energy efficient structure to inject domain walls is provided. Under an applied electric potential, the proposed Π -shaped writing component generates a highly concentrated current distribution. This creates a highly localized magnetic field that quickly initiates the nucleation of a magnetic domain. The formation and motion of the resulting domain walls can then be electrically detected by means of Hall bars (for example made from tantalum) across the nanowire. Measurements show that the Π -shaped writing component can deterministically write a magnetic data bit in 15 ns even with a relatively low current density. Micromagnetic simulations reveal the evolution of the domain nucleation – first, by the formation of a pair of magnetic bubbles, then followed by their rapid expansion into a single domain. Finally, it is demonstrated experimentally that the injection geometry can

perform bit writing using only about 30% of the electrical energy as compared to a conventional injection line.

Figure 6(a) shows the polar Kerr images of a 2 μ m wide PMA nanowire after domain injection while sweeping a small magnetic field. To obtain the Kerr images, a nanowire with an injected domain was imaged from 92–102 Oe in 2 Oe steps. An image of the saturated nanowire was then used for background subtraction. The white (black) contrast represents the up (down) magnetization direction. As shown in Figure 6(a), a magnetic domain was successfully injected into the nanowire underneath the injection line and the domain expands gradually with increasing magnetic field. In a defect-free nanowire, the domain walls will keep moving until they reach the end once the threshold propagation field is reached. However, in this example it was observed that the domain walls were pinned at defects along the nanowire originating from the uneven nanowire sidewalls. The pinning phenomenon was also observed in R_{Hall} measurements of the 350 nm wide nanowire performed with magnetic fields weaker than the saturation field as shown in Figure 6(b). Following the injection of a domain (Fig. 6(c)(i)), the magnetic field was increased from 0–75 Oe. Two distinct R_{Hall} steps at 53 Oe and 59 Oe were observed. This may be attributed to the fact the domain wall has propagated to the Hall bar at 53 Oe (Fig. 6(b)(ii)) and remains pinned until 59 Oe is applied (Fig. 6(b)(iii)). The 6 Oe pinning field may result from the random defects or the interfacial interaction between the nanowire and the heavy metal Ta at the nanowire edge. Due to the device symmetry, only half of the device is shown.

Figure 7 shows a series of curves demonstrating the variation in pulse duration with the probability of successful injection of a domain. The results show that a domain can be injected deterministically in only 8 ns using a relatively low current density of only 4.97×10^{11} A/m². Lowering the current density to 3.6×10^{11} A/m² results in an increased threshold pulse duration t_p of 23ns. The energy required to inject a single magnetic bit can be evaluated by $E = I^2 R t_p$, where I is the current passing through the

injection line and R is the resistance of the injection line. Comparing these results with the typical injection parameters for the prior art method with the straight strip line of 10^{12} A/m² and 14 ns [25-27, 28-31], it can be seen that the magnetic writing component/injection line illustrated in Figures 1 – 3 can be calculated to consume
 5 less than 20% of the energy used in the known method. The relatively low threshold t_p and current density required are attributed to the current density-focusing design of the injection line, in particular the arrangement of the edges 114, 214.

Further data relating to domain injection probabilities are now examined. By
 10 measuring the magnetic field at which R_{Hall} switches, it is possible to determine whether a domain wall has been injected. Subsequently, 10 measurements for each injection current and pulse duration were performed to obtain the domain wall injection probability as shown in Fig. 7(b) and (c). The proposed Π -shaped structure may be able to deterministically inject a domain wall pair in only 15 ns using a low
 15 current density of 5.34×10^{11} A/m². Lowering the current density to 4.1×10^{11} A/m² results in an increased threshold t_p of 50 ns. For the conventional method, the current pulse must be larger than 7.82×10^{11} A/m² with t_p of 70 ns, or increasing the current density to 9.07×10^{11} A/m² results in a decreased t_p of 32 ns. Power consumption, E , for magnetic bit injection can be calculated by $E = I^2 R t_p$, where I is
 20 the current passing through the injection line and R the resistance of the injection line. Thus, our Π -shaped structure is calculated to consume only about 30% of the energy used in conventional method. The relatively low threshold t_p and current density observed in our experiments is attributed to the highly shaped current density and localized magnetic field generated by our proposed injection line.

25

Under an external magnetic field, the rotational behaviour of spins can be modelled by the Landau-Lifshitz-Gilbert equation from where it is possible to obtain [32]:

$$\tan\left(\frac{\theta}{2}\right) = e^{t/\tau} \tan\left(\frac{\theta_0}{2}\right) \quad (2)$$

where ϑ and ϑ_0 is the angle between the magnetic moment and the effective field at t and at $t = 0$, respectively.

$\tau = \frac{1}{\alpha\gamma H_{eff}}$ is the spin lattice relaxation time, where α is the Gilbert damping

5 parameter, γ is the gyromagnetic ratio and H_{eff} is the effective magnetic field which is equal to the in-plane saturation field. After a sufficiently long time $t = 3\tau$, the magnetic moments become almost aligned along the effective field H_{eff} . Using the measured values of $H_{eff} = 3000$ Oe and the values of $\gamma = 2.21 \times 10^5 \text{ m} \cdot \text{A}^{-1}\text{s}^{-1}$ and $\alpha = 0.02$ from [4, 21], the reversal duration was evaluated to be about 2.8 ns for the
10 device under test. To account for the significant difference between the calculated value and experimental observations, further micromagnetic simulations were performed.

Simulating experiments were carried out. Figure 8(a) shows the schematic diagram
15 of the current flow and its corresponding magnetic field. A significant advantage of the Π -shaped writing component is each side of the three segments produce a magnetic field that is oriented in the same direction in the centre, producing an effective magnetic field that is stronger than that of a straight strip line. This compounds the effect of the areas of concentrated distribution arising from the
20 sharp edge geometry. To understand the magnetization reversal processes, COMSOL Multiphysics (TM) simulation software and mumax [3] micromagnetics were used to model the magnetic field distribution at the threshold injection conditions for both the writing component 200 of Figures 2 and 3 and the prior art writing component 602 comprising of a straight strip line, as illustrated in Figure 8(b). The geometry of
25 the devices-under-test was created in COMSOL to accurately model the spatial distribution of the current density and its resultant Oersted field as shown in Fig. 8(c). The threshold current density for deterministic nucleation (J_{th}) at 0 K for deterministic nucleation at 0 K was used. Applying the electrical currents with a rise time of 300 ps in mumax [3], J_{th} was determined to be 220 mA and 129 mA,

corresponding to an average current density of $2.9 \times 10^{12} \text{ A/m}^2$ and $1.7 \times 10^{12} \text{ A/m}^2$, respectively. Where applicable, the cones indicate the in-plane orientation of the vector fields.

- 5 From the simulations, it is clear that the Π -shaped injection line has another two advantages. Firstly, as the Oersted field decays with distance squared, electrical current far away from the nucleation site does not contribute significantly to the Oersted field at the nucleation site. The highly angular design minimizes this type of inefficiency by focusing the current into a narrow region that creates a strong and
- 10 localized magnetic field at the nucleation site. Secondly, while a threshold magnetic field is required to initiate domain wall nucleation, that magnetic field need not be acting uniformly on the magnetic nanowire. A small localized region of high magnetic field can also initiate the nucleation of a small metastable domain which will easily spread out to form a larger and more stable domain. This is more efficient than
- 15 applying a uniform magnetic field to nucleate a domain.

On the bottom right side of Fig. 8(c), the time resolved magnetization dynamics of the Π -shaped injection geometry is shown. Upon application of a magnetic field with a 300 ps rise time, spin wave excitations were observed. After a few oscillations, two

- 20 metastable magnetic bubble domains are nucleated at the position of the localized magnetic field. The two domains eventually expand in size with the assistance of the Oersted field and form a complete domain wall pair after 600 ps. Given sufficient time for the magnetization to relax, it is apparent that the Π -shaped injection geometry produces a narrower domain.

25

While these simulations showed that a short but strong current pulse can nucleate a domain, experimental injection typically requires a relatively low current density of $\sim 10^{11} \text{ A/m}^2$ and pulse width of $\sim 10 \text{ ns}$. One possible explanation for the difference is likely to originate from the relatively high temperatures that are generated by the

- 30 significant Joule heating. To study the effects of temperature, the pulse duration

required for deterministic domain wall injection as a function of current density for the two injection line geometries and at different temperatures was simulated as shown in Fig. 9(c). Temporally static and spatially uniform temperature distributions were considered. With the addition of a randomly fluctuating thermal field [33], t_p for different simulation runs were found to differ. Therefore, the average of 25 injection attempts was used and their standard deviation is shown as the error bars.

As the temperature was increased, t_p and J_{th} were found to decrease; i.e. less energy was required for domain injection. Figure 9(d) shows the injection current density as a function of temperature. The J_{th} at 1000 K was found to be about 39% lesser than at 0 K. Comparing these simulation results with experimental observations, t_p was found to be much shorter (~ 3 ns versus ~ 10 ns) and J_{th} was found to be much larger ($\sim 1 \times 10^{12}$ versus $\sim 5 \times 10^{11}$). It is likely that the Joule heating resulting from a current lower than the J_{th} will first heat up the nanowire beneath [34], with magnetization reversal occurring only when a sufficiently high temperature is reached. The proposed injection mechanism not only explains for the low current and high t_p reported in literature but could also play an important role in the energy consumption of domain injection processes.

The numerical calculations in Figures 9(c) and (d) also show that the design markedly decreases the current required for domain wall injection. Fitting in the threshold conditions at 300 K, it is calculated that the proposed injection method only consumes 24% of the energy used in known injection lines. For the other temperatures, the energy consumption were also calculated to be around 30%, agreeing well with the experimental results. The large energy savings presented here will not only path the way to energy efficient magnetic memory devices but also improve data stability by limiting Joule heating in the nanowires.

Coming back to Figure 8(b), this illustrates the current density distribution in the writing component/injection line 200, particularly the areas 600 of concentrated

current distribution appearing at the sharp edges defined by the geometry of the writing component, in comparison to the uniform current density distribution in the known straight strip line 602. Figure 8(c) illustrates a comparison between known strip line 602 and the magnetic writing component 200 of Figures 2 and 3 for the Z-axis magnetic field, with the magnetic field acting on the magnetic material. The magnetization dynamics shown in Figure 8(d) during the domain wall nucleation process illustrates that while a threshold magnetic field is required to initiate domain wall nucleation, the magnetic field need not be acting uniformly on the memory component/magnetic nanowire. A localized region of high magnetic field, even a small one, can also initiate spin flipping which will eventually spread out to form a larger and more stable domain. The magnetic writing component of Figures 2 and 3 may be used to create an extremely localized magnetic field at each side of the memory component/nanowire 112 to nucleate a metastable magnetic domain. Only a much weaker magnetic field is needed for the expansion of such magnetic domains. Therefore, the magnetic domain formed can expand quickly to form a domain wall pair by the end of the injection pulse.

Thus, from the experiments, it can be seen that the comparative advantage of magnetic writing components of Figures 1 – 3 over a known writing component such as the straight strip line 602 to produce magnetic field pulses is apparent in one or more of three significant areas:

- Firstly, the sharp bends in the writing component/injection lines 100, 200 focus the electric current, allowing a thicker injection line to achieve the current density distribution of a much finer nanowire, without suffering from the negative effects of Joule heating, and the manufacturing difficulties surrounding the formation of the finer nanowire. A focused current is more desirable as the produced magnetic field quickly decays with distance.
- Secondly, as compared to the known straight strip line design, the magnetic field produced by the writing components 100, 200 is highly asymmetrical.

This may result in the creation of only one nucleation point when an appropriate current density is used. In contrast, the magnetic field produced on both sides of the known injection line is equal and opposite in magnitude, possibly affecting neighboring magnetic bits.

- 5 • Thirdly, the writing components 100, 200 can create intense and localized magnetic fields to initiate magnetization reversal, instead of creating uniform magnetic fields of the same magnitude. This results in the better energy efficiency seen in the experiments described above. Indeed, Figure 9 shows the threshold injection parameters derived from micromagnetic simulations
- 10 for the writing component 200 and the known straight strip line designs. Figure 9(a) shows the threshold injection parameters t_p and current density as a function of each other and also temperature. Figure 9(b) shows the injection current needed for the magnetic bit writing at different
- 15 temperatures. Across all temperatures, the novel design of writing component 200 is shown to require less energy for magnetic bit writing in a domain wall memory type device.

Generally speaking, these advantages also hold true for the writing component 100 of Figure 1.

20

- On smaller length-scales, the novel design of the writing components of Figures 1 – 3 operate similarly and retain the same advantageous performance characteristics. Figure 10 shows the current density distribution and z-axis magnetic field profile resulting from various modifications of the proposed designs for the writing
- 25 components/injection lines 100, 200 while keeping the injection line width constant at 30 nm and the current at 1 mA. As shown in Figure 10(a), a Λ -shaped injection line can create a single localized magnetic field, useful at the 30 nm length-scale where the nucleation of only a single domain is required. The remaining arrangements of Figures 10(b) – (f) show how the varying degree of edge roundedness can affect the
- 30 magnetic field profile. For instance, Figure 10(b) illustrates the performance of a Π -

- shaped magnetic writing component 200 with sharp or substantially sharp edges. Figures 10(c) – (e) illustrate the performance with rounded edges of increasing radius, respectively with a 5 nm radius in (c), a 10 nm radius in (d) and with a 15 nm radius in (e). With increasing rounding, the focusing effect is diminished and the two localized magnetic field regions gradually merge into a single larger magnetic field. However, even in the case of Figure 10(e), this design still exhibits the advantageous characteristics that allow it to be more efficient than the known design illustrated, for comparison's sake, in Figure 10(f).
- 10 The techniques described above for the injection of magnetic bits into PMA materials can be used to enhance the energy efficiency of several magnetic random access memory (MRAM) technologies that utilize domain walls. One such technology is the three-terminal magnetic tunnel junction (MTJ), as illustrated in Figure 12. In the illustrated MTJ, the domain wall position determines the tunneling
- 15 magnetoresistance (TMR). This device is therefore a form of non-volatile analog memory and also naturally a promising candidate for neuromorphic computing. By first injecting a domain and then shifting the domain wall to various positions in the MTJ free layer, the tunneling magnetoresistance of the MTJ can be changed in an analog manner [13 - 15]. Another type of MTJ device is the four terminal MTJ used
- 20 for logic applications. The device uses domain wall motion to switch between the MTJ states. This type of MTJ has the advantage of being all-metallic and does not require large write currents to pass through the metal oxide tunnel barrier [15]. In these devices, the current techniques used to inject domain walls into the MTJ devices utilizes a straight injection line [15], which can easily be replaced with, for
- 25 example, the Π -shaped magnetic writing component/injection line 200 for a better energy efficiency and with less stochasticity as shown in Figure 11. In Figure 11, the MTJ device comprises a metal oxide and top electrode 1100, the memory component 112 (also a nanowire in this example) and the magnetic writing component/injection line 200 of Figure 2. For comparison's sake, the known
- 30 arrangement is illustrated having a known straight strip line 1102. The domain is

nucleated under the injection line and can be shifted within the magnetic nanowire. Depending on the ratio of the magnetization under the top electrode, the resistance can be varied. The application is general to all types of domain wall based MTJs including for neuromorphic memory or magnetic logic applications.

5

Another MRAM technology which may benefit from the Π -shaped writing component/injection line 200 is the Toggle MRAM as illustrated in Figure 13 made commercially available by EverSpin. In the one transistor, one MTJ Toggle MRAM cell, a pair of injection lines produces orthogonal magnetic fields that flip the magnetization of the magnetic free layer as shown in the figure. This is in contrast with the spin transfer torque MRAM in which the free layer is switched by the spin transfer torque from the spin polarized current acting on the magnetic free layer. In Toggle MRAM, most of the write power is dissipated by the injection line. Therefore the use of the Π -shaped writing component/injection line instead of a known straight injection line for magnetic field generation may reduce the current densities required to switch an MRAM cell, and in the process greatly reducing power consumption while likely also decreasing device footprint.

In conclusion, it will be seen that a highly angular Λ -shaped and Π -shaped injection lines are proposed and demonstrated to be highly efficient at the injection of data bits into perpendicular magnetic anisotropy magnetic nanowire. The structure of the writing component proposed strip line generates a highly shaped electric current which in turn generates an extremely localized field. Under such intense magnetic fields, a pair of magnetic bubble domains nucleates and quickly grows into a magnetic domain in the nanowire underneath. Experiments show that these techniques can deterministically write a magnetic data bit using only a 15 ns pulse with a current density of $5.34 \times 10^{11} \text{ A/m}^2$. Both experiments and simulations show that the writing component design may require about 30% of the energy for bit writing as compared to non-designs. Furthermore, the simple design of the writing

components ensures their compatibility with current domain wall device designs, allowing for widespread adoption.

Methods

5 **Film deposition.** A silicon wafer with a 300-nm-thick SiO₂ layer was used as a substrate. Co/Ni multilayer was deposited using DC magnetron sputtering deposition technique at room temperature. The stack structure was, from the substrate side, Ta(5 nm)/Pt(5 nm)/[Co(0.25 nm)/Ni(0.5 nm)]₄/Co(0.25 nm)/Ta(5 nm).

Device fabrication. The device was fabricated in three processes: first, the 350 nm wide nanowire was patterned by electron beam lithography and Ar ion milling from the Co/Ni multilayer film. Secondly, two Ta(10 nm) hall bars were patterned using electron beam lithography technique followed by resist lift-off. Third, Ta(6 nm)/Cu(94 nm)/Au(24 nm) electrodes as well as the injection line were also fabricated using electron beam lithography technique and lift-off. Argon reverse sputtering was employed before the second and third processes to obtain a better Ohmic contact.

Electrical measurement. The Hall resistance measurements and domain wall injection were carried out on a Cascade Microtech probe station. A Picosecond 10300B pulse generator was used to inject domain walls by applying pulsed current from E to E'. The Hall resistance is determined by measuring the voltage with a Keithley 2000 between electrodes C and D while applying a constant DC current of 50 µA with Keithley 2400 along the nanowire. All measurements were performed at room temperature.

Simulations. COMSOL Multiphysics was used to accurately model the current density distribution and its resultant Oersted field by solving the following set of equations:

$$\nabla \cdot (\sigma E + J_e) = Q_j \quad (3)$$

$$E = -\nabla V \quad (4)$$

$$\nabla \times (\mu^{-1} \nabla \times A) = J_e \quad (5)$$

$$B = \nabla \times A, \quad (6)$$

$$\mathbf{H} = \mu^{-1} \times \mathbf{B} , (7)$$

Where μ is the permeability, σ is the conductivity, V is the electric potential, J_e is the current density, $\mathbf{A}$ is the magnetic vector potential, $\mathbf{H}$ is the magnetic field and $\mathbf{B}$ is the magnetic flux density.

5

Mumax [3] was used to perform the micromagnetic simulation by numerically solving the Landau-Lifshitz-Gilbert (LLG) equation:

$$\frac{d\mathbf{m}}{dt} = \gamma \mathbf{H}_{eff} \times \mathbf{m} + \alpha \mathbf{m} \times \frac{d\mathbf{m}}{dt} , (8)$$

- 10 where $\mathbf{m}$ is the unit vector of the local magnetization, γ is the gyromagnetic ratio, $\mathbf{H}_{eff}$ is the effective magnetic field, α is the Gilbert damping parameter. The unit cell size is set to 5 nm × 5 nm × 3.25 nm. The material parameters were chosen for Co/Ni: [21] the anisotropy constant, $K_u = 3.8 \times 10^5$ J/m³, saturation magnetization $M_s = 6.8 \times 10^5$ A/m and the exchange stiffness constant $A = 1 \times 10^{-11}$ J/m. The damping
- 15 constant value $\alpha = 0.02$. For the DW injection, the rise time was taken to be 300 ps.

It will be appreciated that the invention has been described by way of example only and that various modifications may be made to the techniques described above without departing from the spirit and scope of the invention.

20

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CLAIMS

1. A magnetic memory device comprising:
a memory component comprising perpendicular magnetic anisotropy, PMA,
5 material;
a writing component comprising electrically-conductive material, the writing component being for writing a magnetic data bit in the PMA material, the writing component comprising a first segment and a second segment, the first segment and the second segment meeting at an edge section, the edge section being disposed
10 facing the PMA material; and wherein
the magnetic memory device is configured to inject an electrical pulse into the writing component for the generation of a localised magnetic field component from the edge section.
- 15 2. The magnetic memory device of claim 1, wherein the edge section comprises a sharp edge defining a boundary between the first segment and the second segment of the writing component.
3. The magnetic memory device of claim 1, wherein the edge section comprises
20 a rounded edge where the first segment and the second segment of the writing component meet.
4. The magnetic memory device of any preceding claim, wherein the first segment and the second segment extend, at an angle with respect to each other,
25 away from the edge section, thereby forming a volume defined in part by the first segment and the second segment in which a portion of the memory component is disposed.
5. The magnetic memory device of any of claims 1 to 3, wherein the writing
30 component comprises a third segment, the first segment and the third segment

extending generally perpendicularly from the second segment, thereby forming a volume defined in part by the first segment, second segment and third segment in which a portion of the memory component is disposed.

5 6. The magnetic memory device of any preceding claim, wherein the memory component comprises a nanowire in a magnetic random access memory device.

7. The magnetic memory device of any preceding claim, wherein the memory component comprises a free layer in a magnetic tunnel junction device.

10

8. A method of writing a magnetic data bit in a magnetic memory device, the magnetic memory device comprising:

 a memory component comprising perpendicular magnetic anisotropy, PMA, material; and

15 a writing component comprising electrically-conductive material, the writing component comprising a first segment and a second segment, the first segment and the second segment meeting at an edge section, the edge section being disposed facing the PMA material, the method comprising:

 injecting an electrical pulse into the writing component to generate a
20 localised magnetic field component from the edge section.

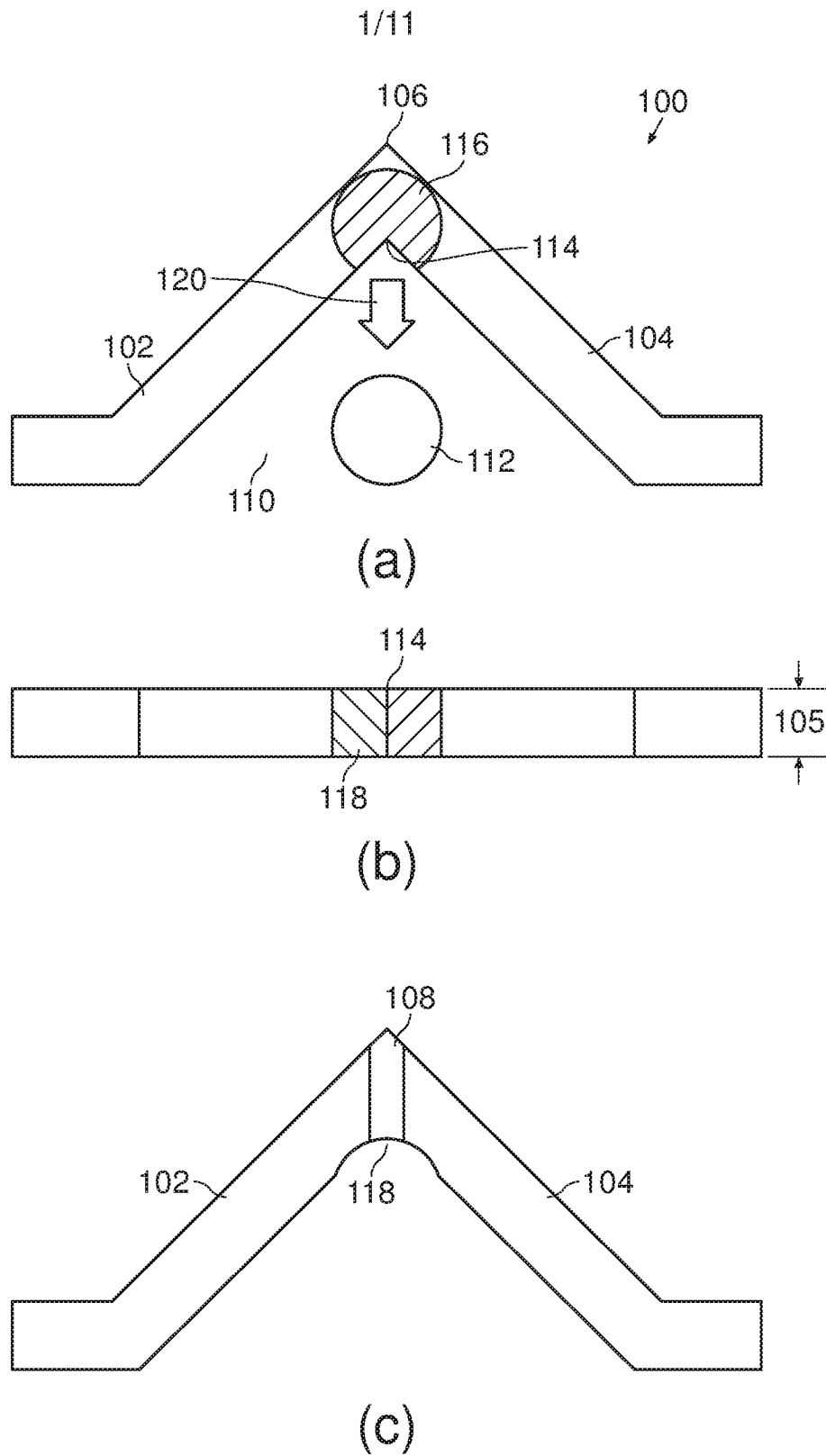


FIG. 1

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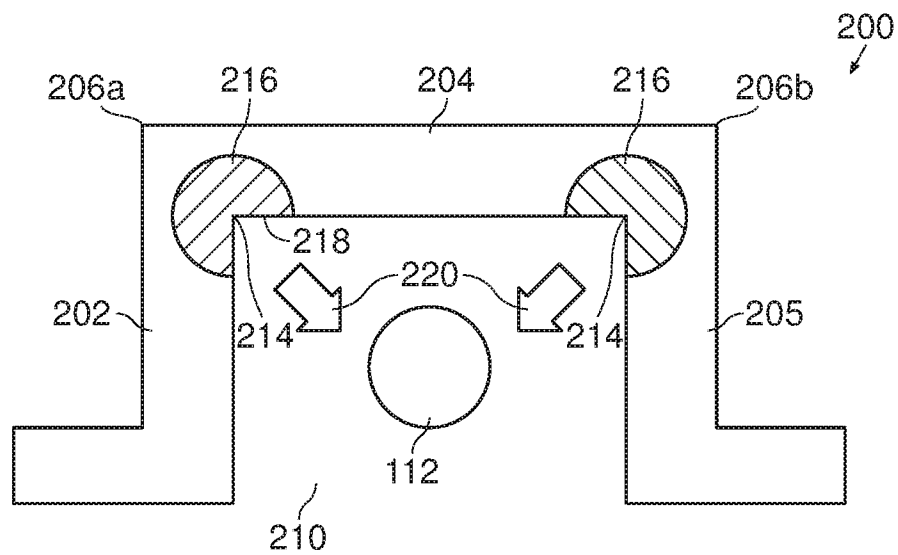


FIG. 2

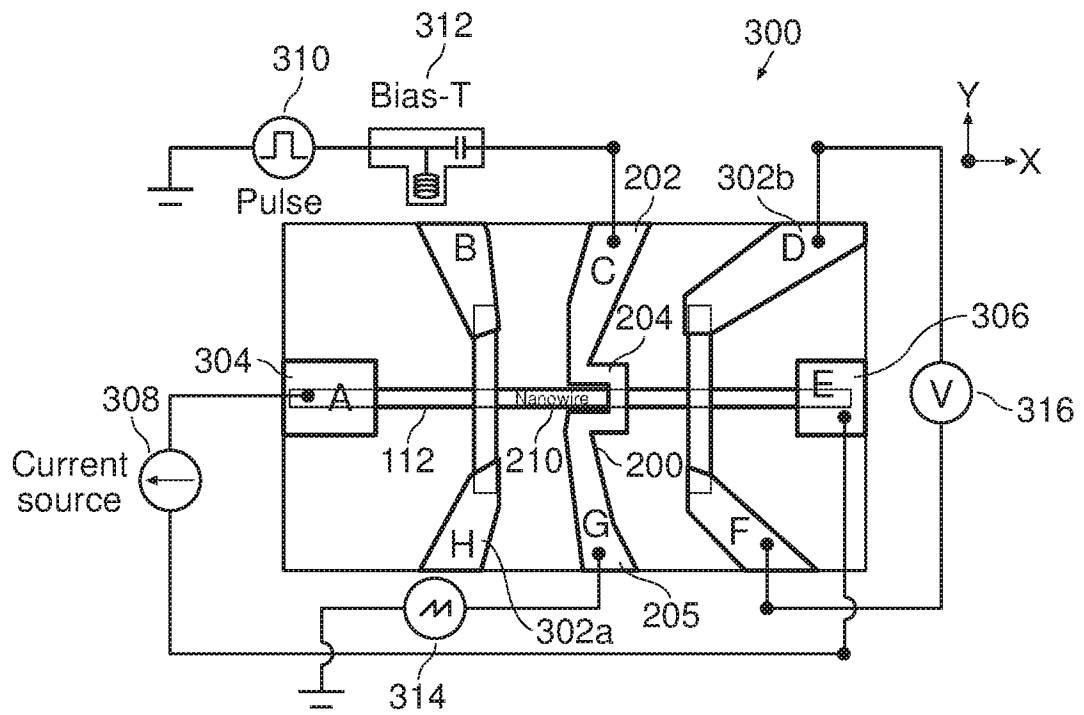


FIG. 3

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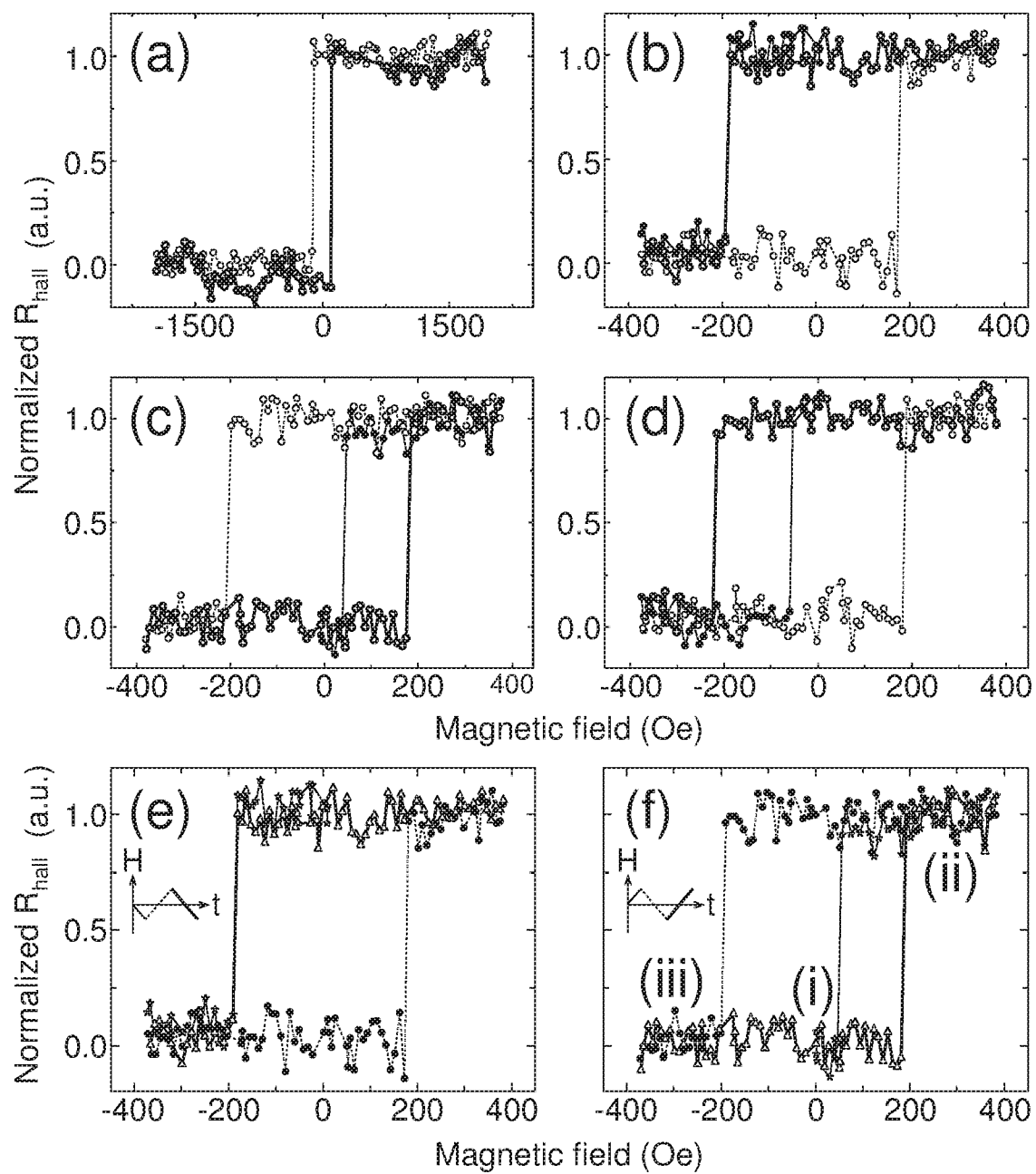


FIG. 4

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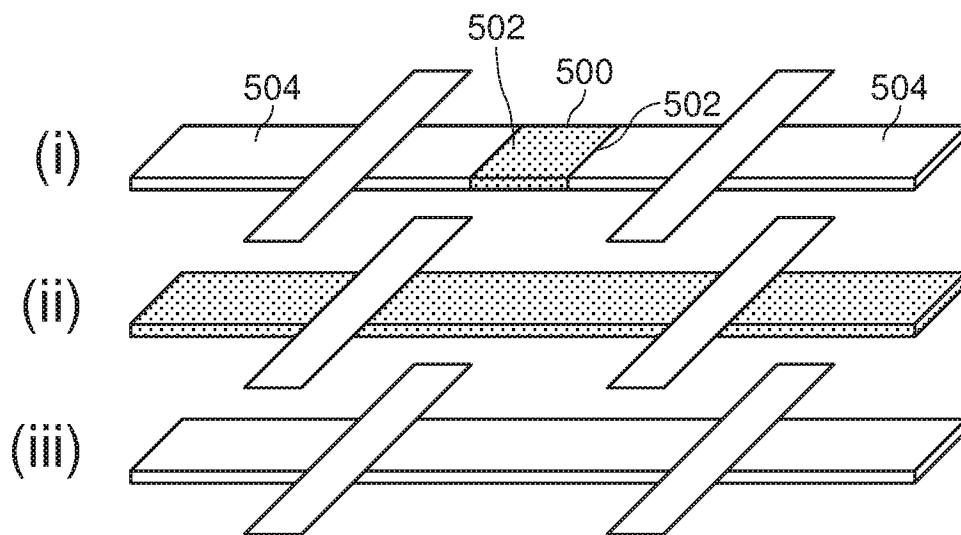


FIG. 5

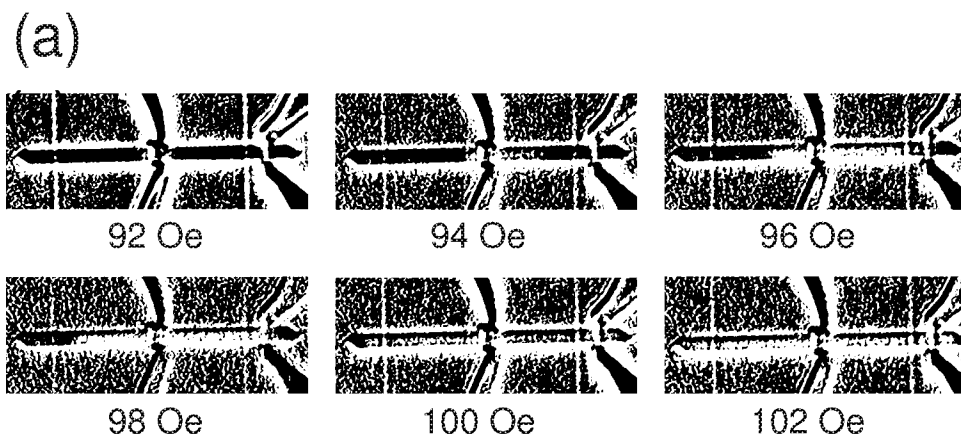


FIG. 6

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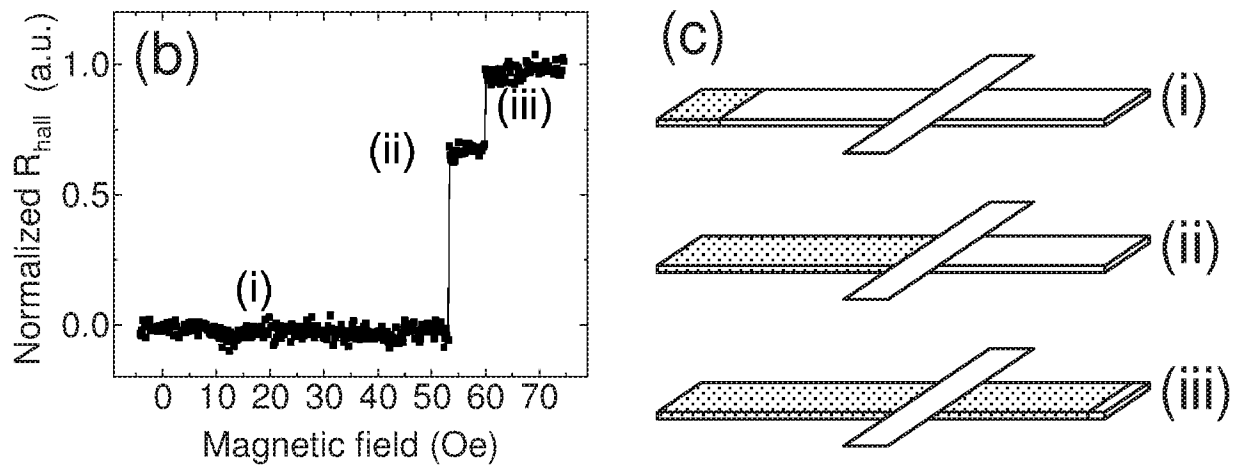


FIG. 6

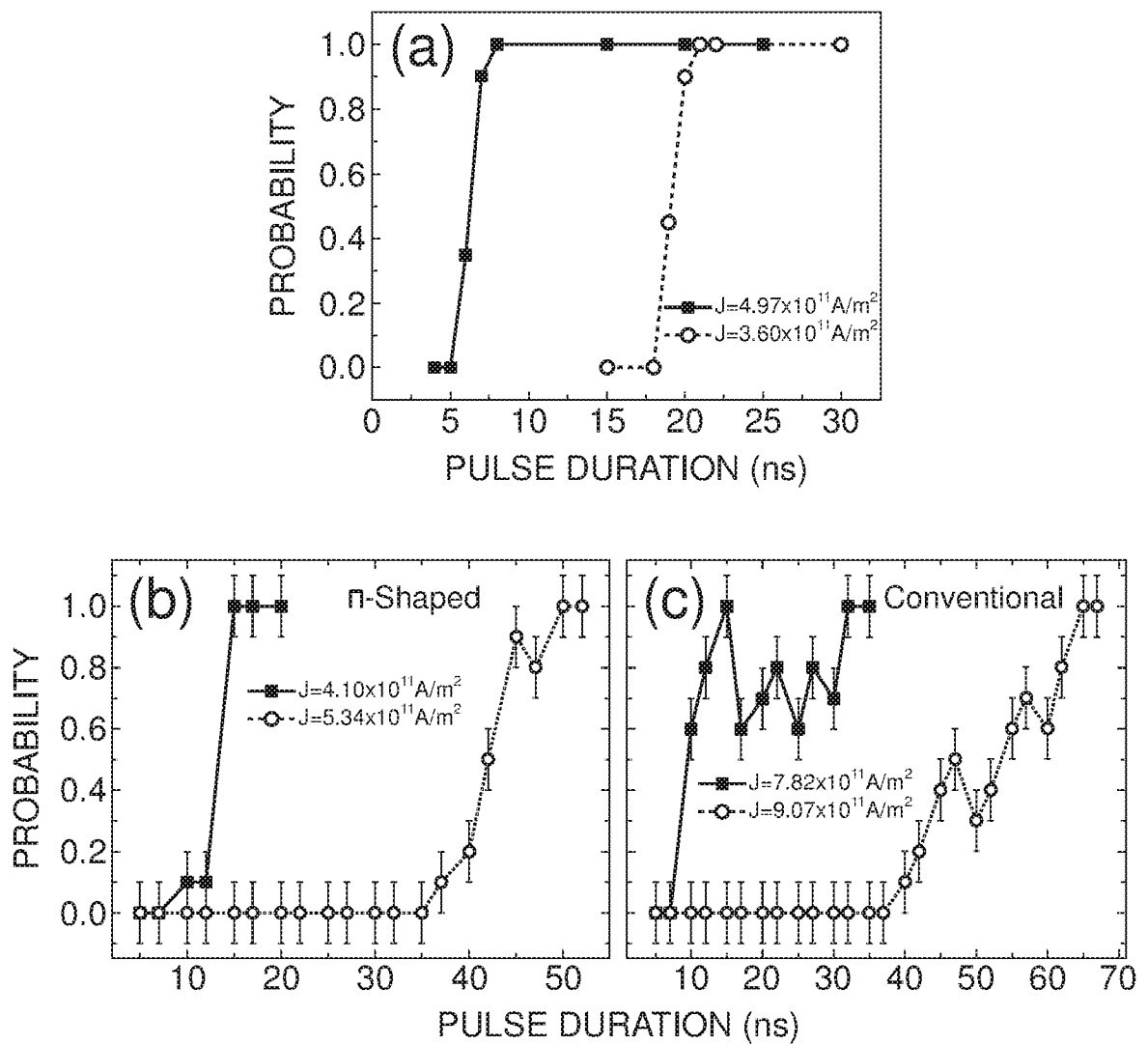


FIG. 7

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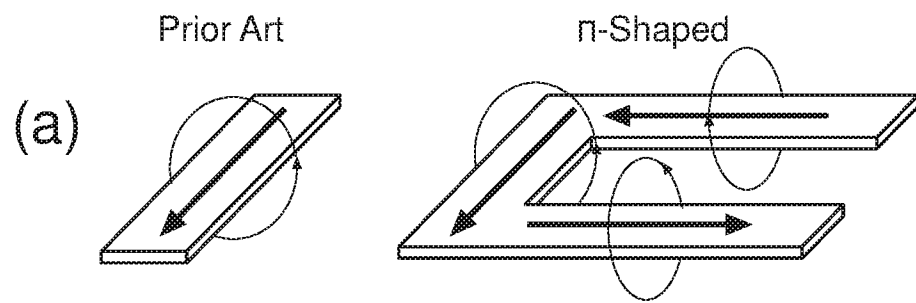


FIG. 8

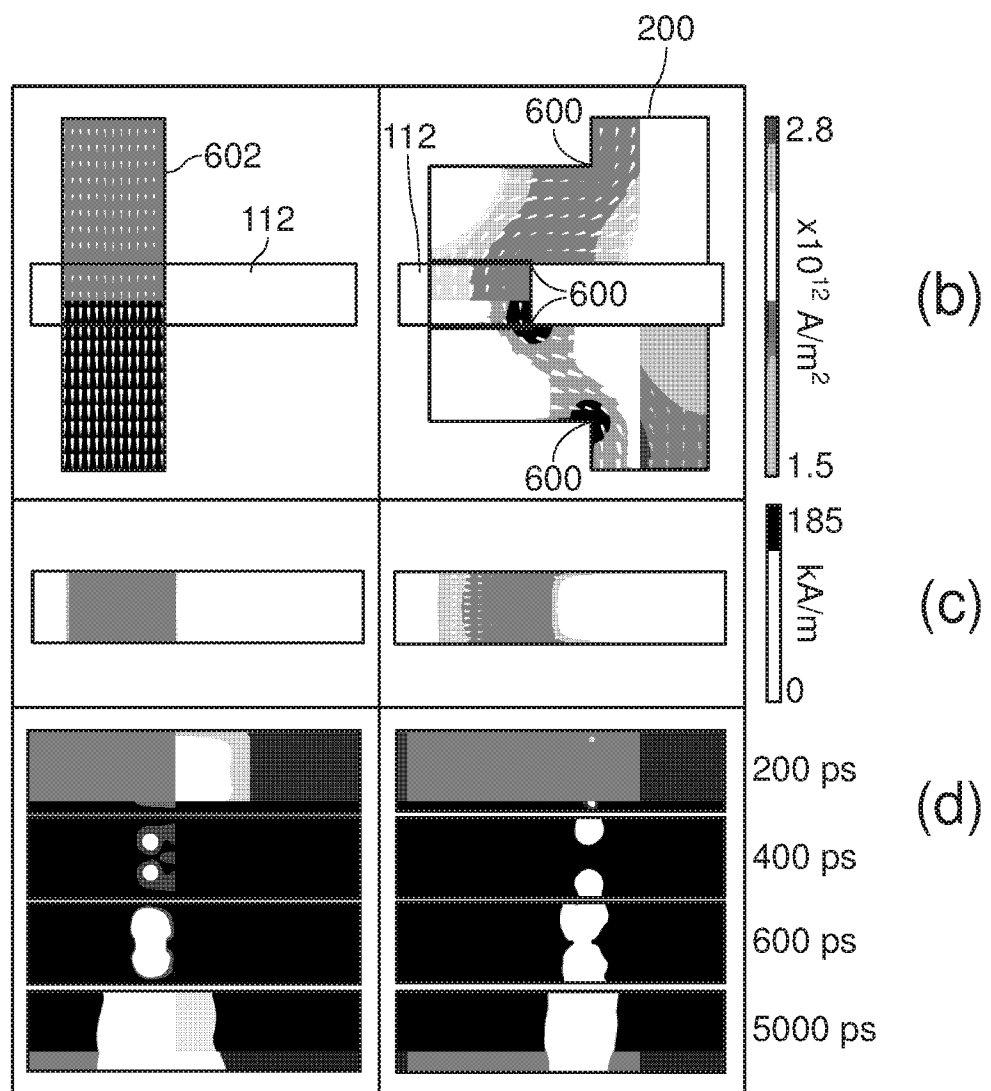


FIG. 8

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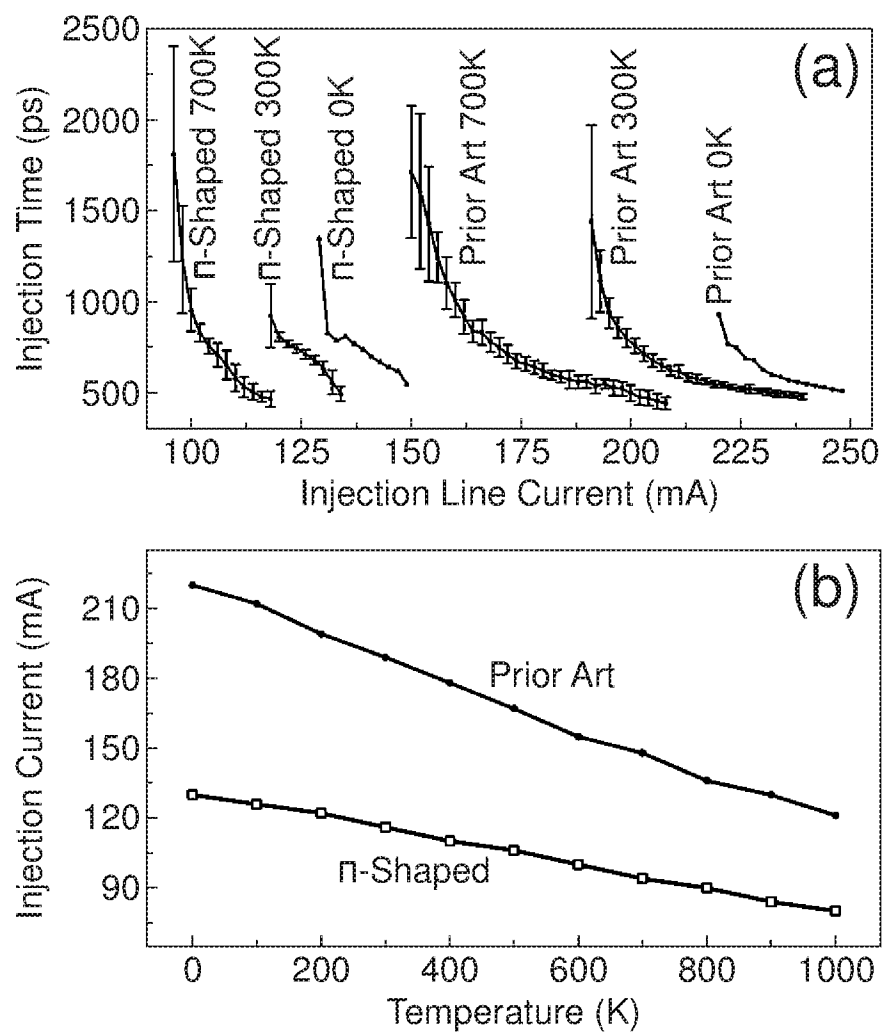


FIG. 9

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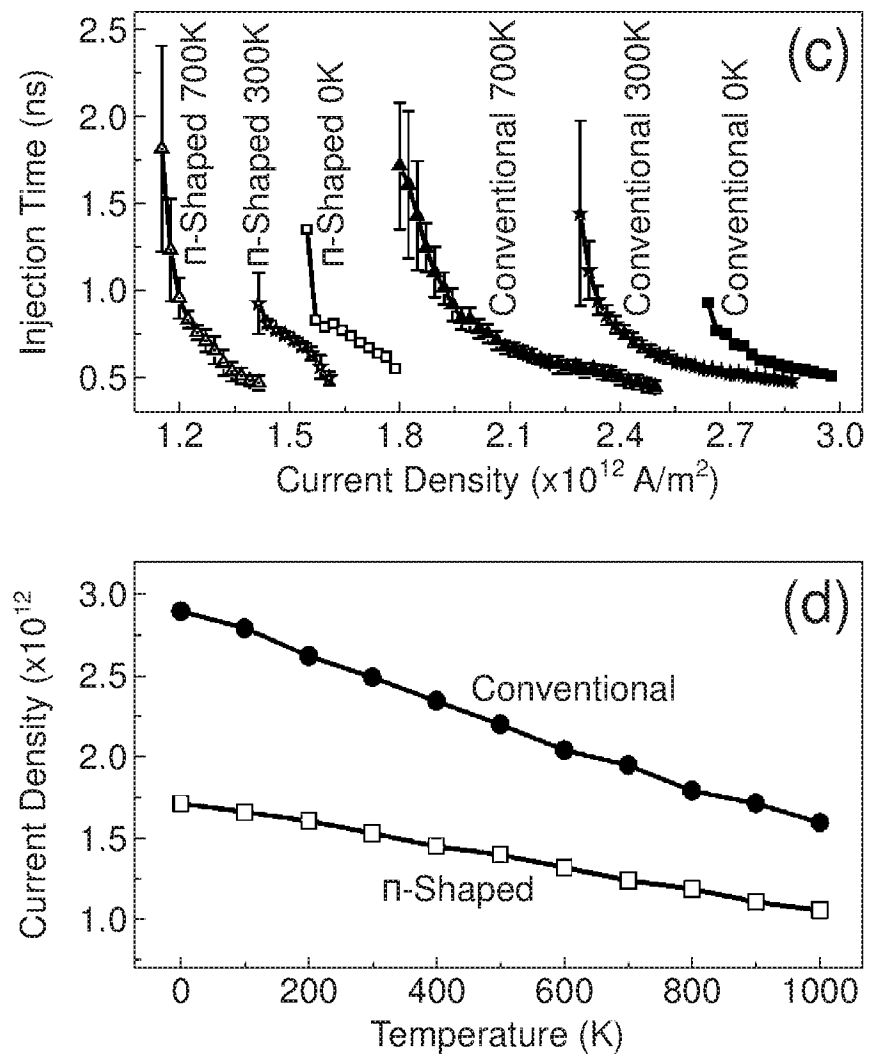


FIG. 9

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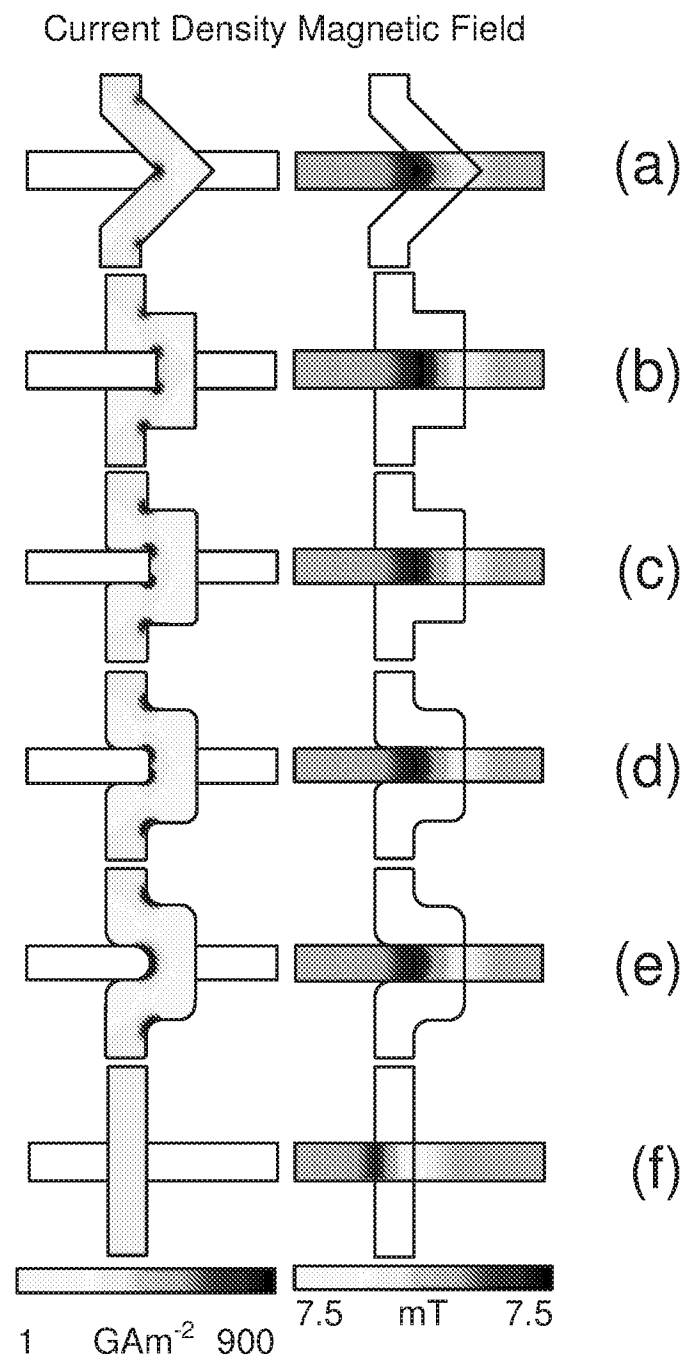


FIG. 10

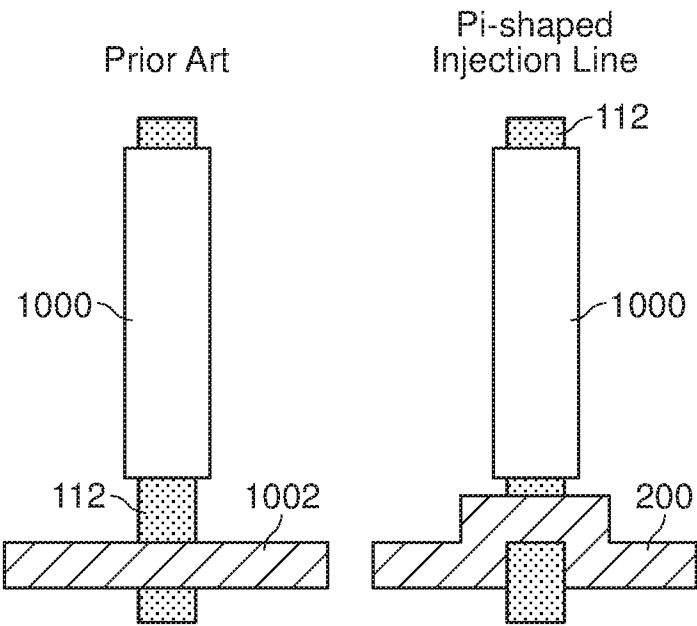


FIG. 11

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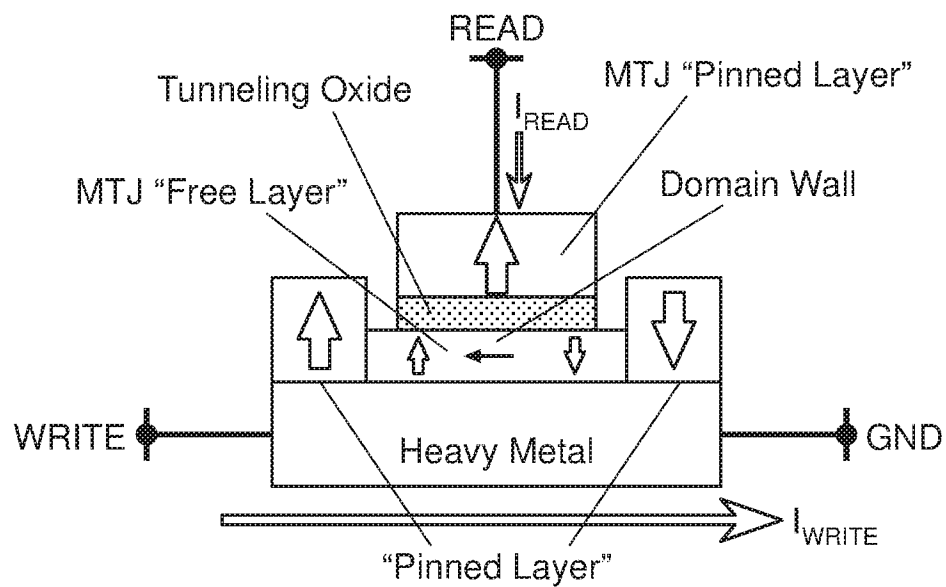


FIG. 12

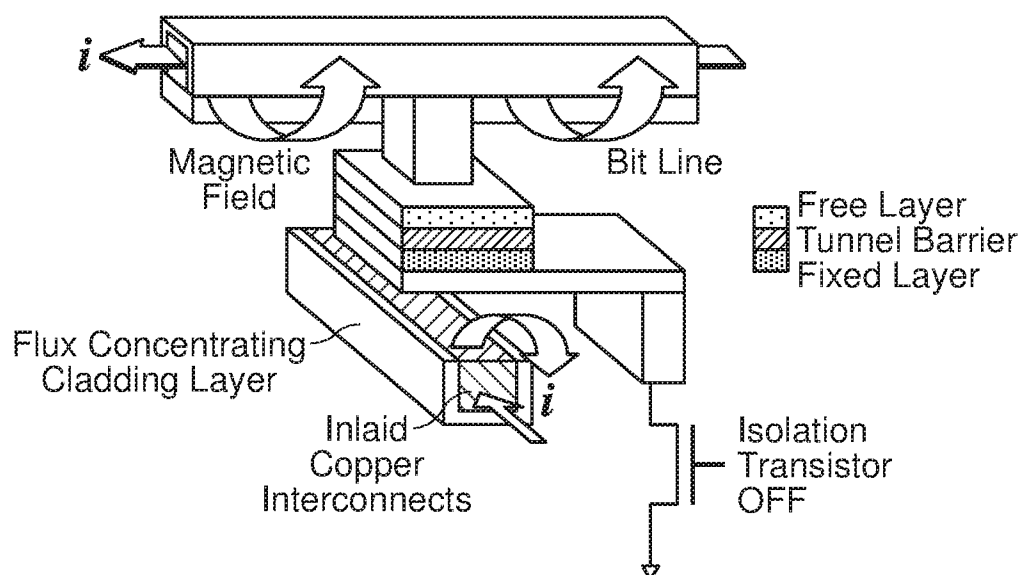


FIG. 13

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2016/050526

A. CLASSIFICATION OF SUBJECT MATTER

G11C 19/02 (2006.01) G11C 11/16 (2006.01)

According to International Patent Classification (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)

FAMPAT, IEEE, Scopus: domain, edge, nanowire, current density, PMA, MRAM, Oerstad and other related terms

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2008/0239784 A1 (GAIDIS, M. C. ET AL.) 2 October 2008 Paragraphs [0008], [0022]-[0024], [0033]; Figures 2 and 6	1-8
A	US 2014/0268982 A1 (ANNUNZIATA, A. J. AND GAJEK, M. J.) 18 September 2014 Paragraphs [0014], [0018]; Figure 1	
A	CHIBA, D. ET AL., Control of Multiple Magnetic Domain Walls by Current in a Co/Ni Nano-Wire. <i>Applied Physics Express</i> , 2 July 2010, Vol. 3, No. 7, pages 073004:1-3 [Retrieved on 2016-12-23] <DOI: 10.1143/APEX.3.073004> Pg. 1 left column 1st paragraph; Figure 1	
A	HAN, G. C. ET AL., Perspectives of Electric Field Controlled Switching in Perpendicular Magnetic Random Access. <i>IEEE Transactions on Magnetics</i> , 18 May 2015, Vol. 51, No. 4, pages 1-9 [Retrieved on 2016-12-23] <DOI: 10.1109/TMAG.2014.2354452> Whole document	

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

*Special categories of cited documents:

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"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

27/12/2016

(day/month/year)

Date of mailing of the international search report

31/01/2017

(day/month/year)

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/SG2016/050526

Note: This Annex lists known patent family members relating to the patent documents cited in this International Search Report. This Authority is in no way liable for these particulars which are merely given for the purpose of information.

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