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Kazemi et al.

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- (54) **SWITCHING OF PERPENDICULARLY MAGNETIZED NANOMAGNETS WITH SPIN-ORBIT TORQUES IN THE ABSENCE OF EXTERNAL MAGNETIC FIELDS**
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(Continued)

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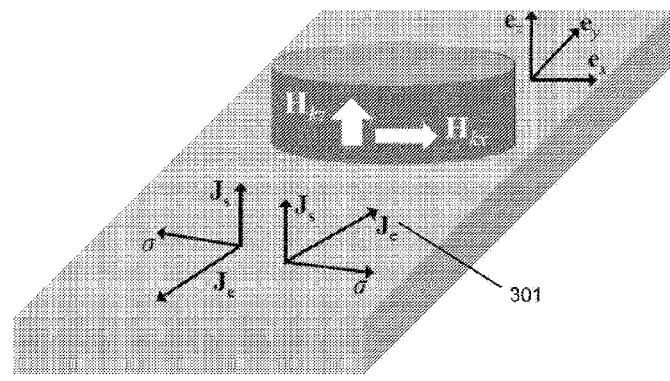
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(57) **ABSTRACT**
A base element for switching a magnetization state of a nanomagnet includes a heavy-metal strip having a surface. A ferromagnetic nanomagnet is disposed adjacent to the surface. The ferromagnetic nanomagnet has a first magnetization equilibrium state and a second magnetization equilibrium state. The first magnetization equilibrium state or the second magnetization equilibrium state is settable in an absence of an external magnetic field by a flow of electrical charge through the heavy-metal strip. A method for switching a magnetization state of a nanomagnet is also described.

21 Claims, 5 Drawing Sheets



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H01L 43/10 (2006.01)
- (52) **U.S. Cl.**
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- (58) **Field of Classification Search**
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See application file for complete search history.

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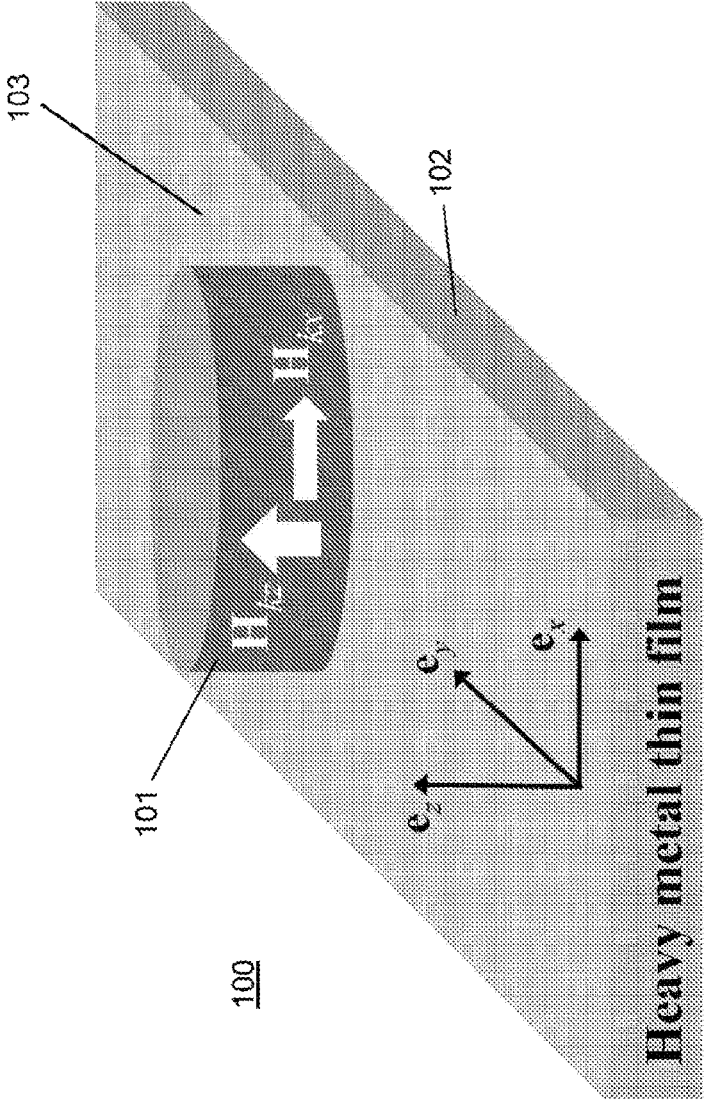


FIG. 1

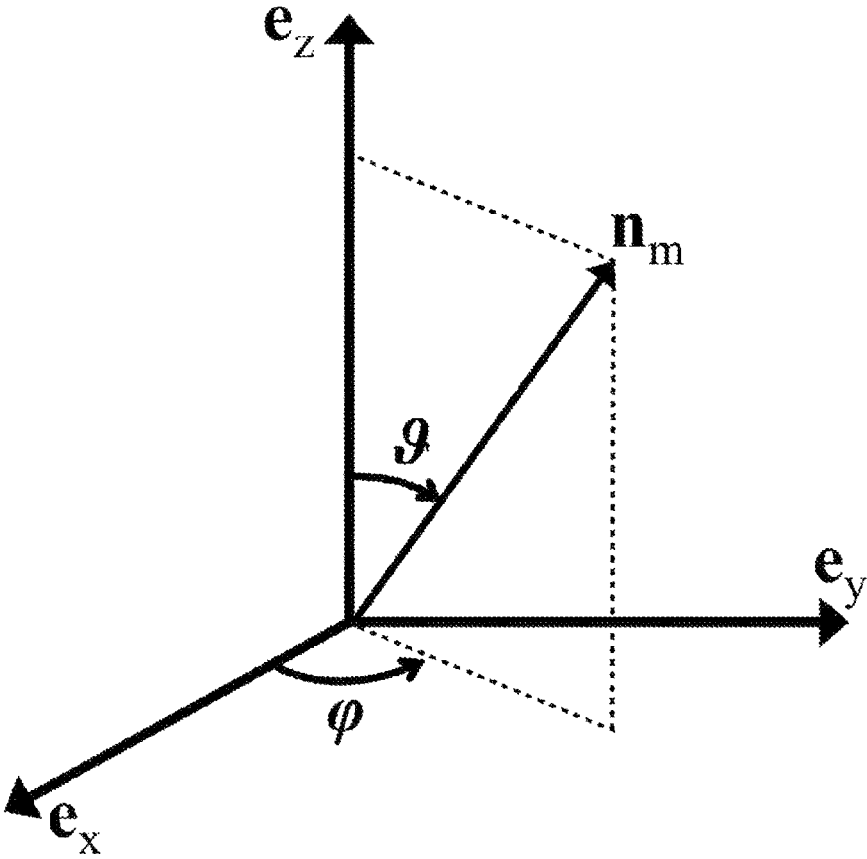


FIG. 2



FIG. 3B

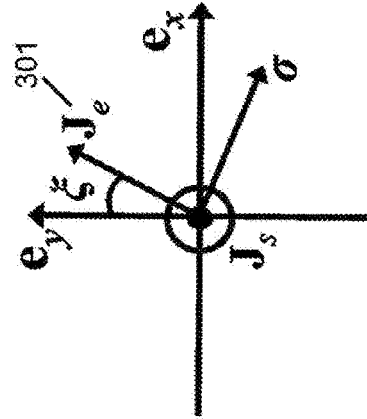


FIG. 3C

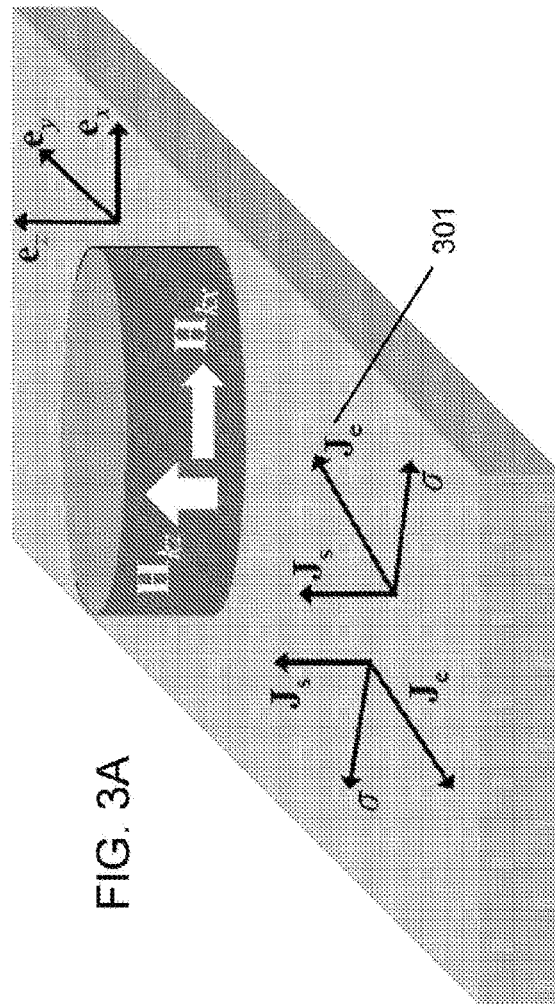


FIG. 3A

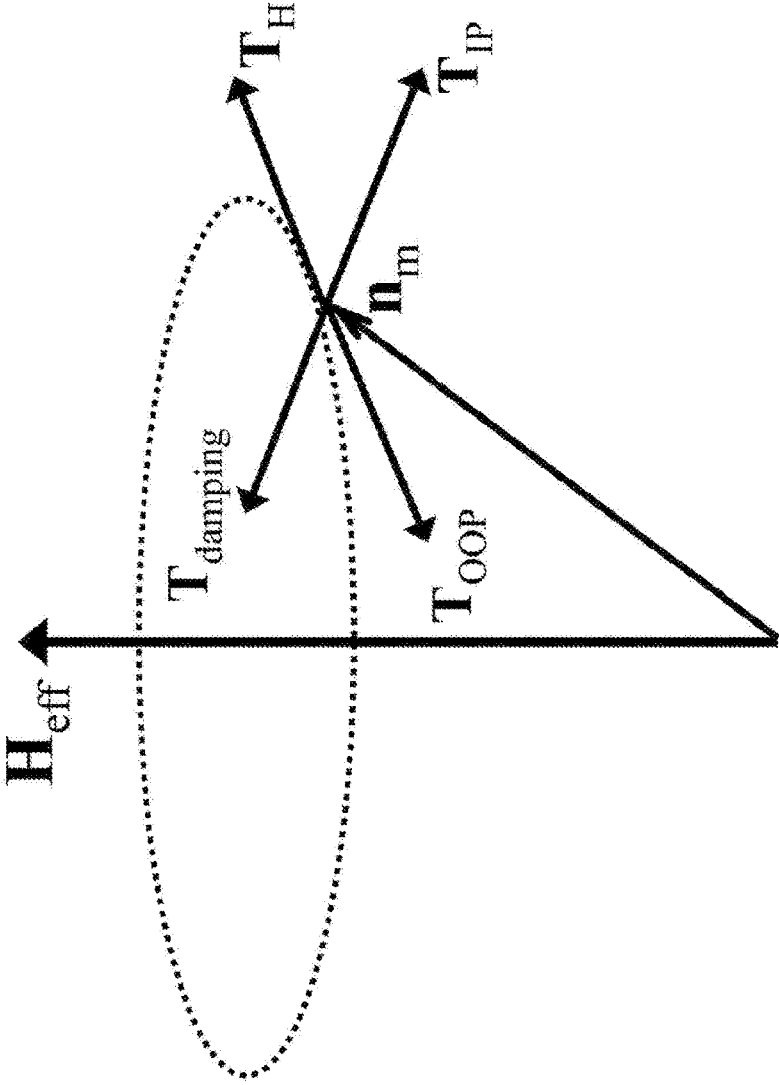


FIG. 4

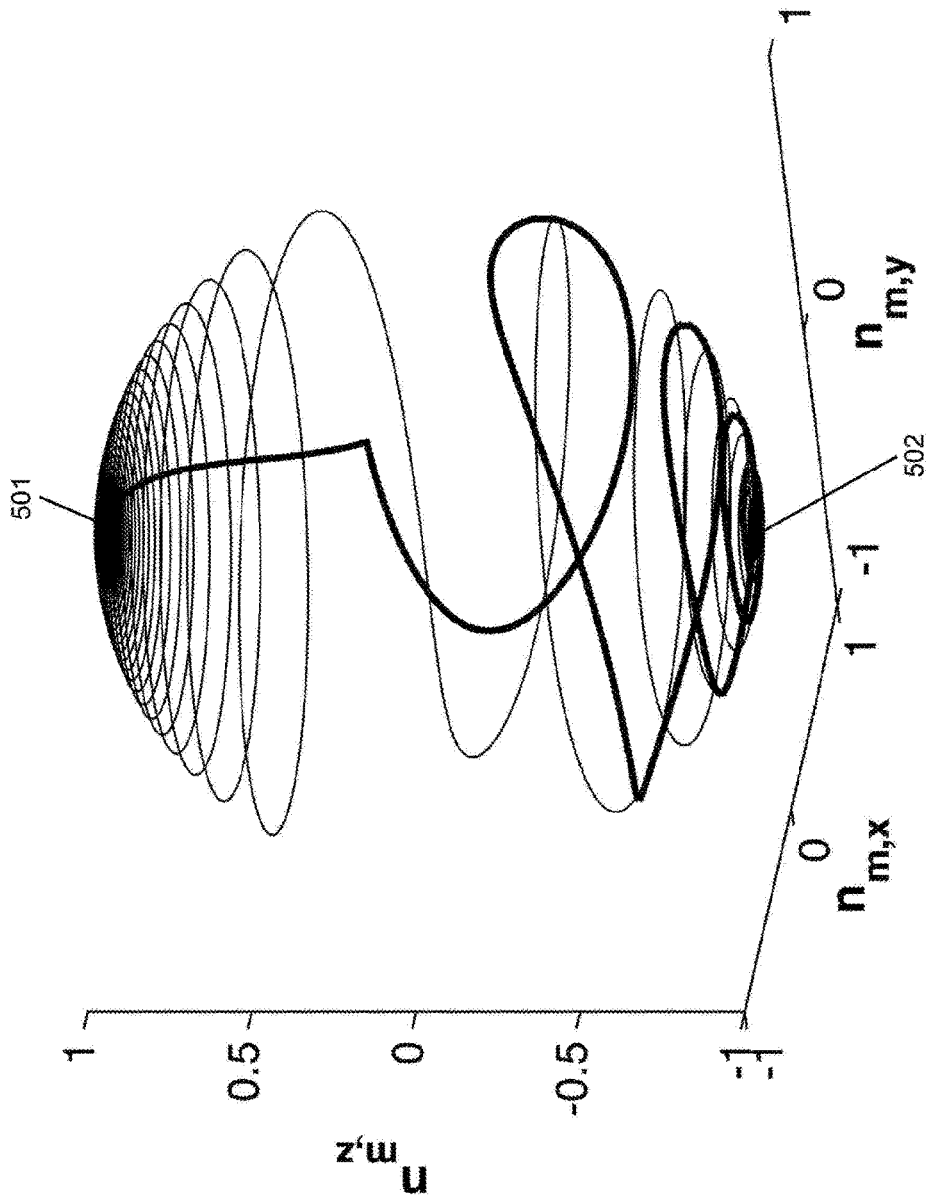


FIG. 5

**SWITCHING OF PERPENDICULARLY
MAGNETIZED NANOMAGNETS WITH
SPIN-ORBIT TORQUES IN THE ABSENCE
OF EXTERNAL MAGNETIC FIELDS**

CROSS-REFERENCE TO RELATED
APPLICATIONS

This application is a national stage application under 35 U.S.C. § 371 of PCT Application No. PCT/US16/28045, filed Apr. 18, 2016, SWITCHING OF PERPENDICULARLY MAGNETIZED NANOMAGNETS WITH SPIN-ORBIT TORQUES IN THE ABSENCE OF EXTERNAL MAGNETIC FIELDS, published as WO2016190984 A2, which claims priority to and the benefit of U.S. provisional patent application Ser. No. 62/158,805, SWITCHING OF PERPENDICULARLY MAGNETIZED NANOMAGNETS WITH SPIN-ORBIT TORQUES IN THE ABSENCE OF EXTERNAL MAGNETIC FIELDS, filed May 8, 2015, which applications are incorporated herein by reference in their entirety.

STATEMENT REGARDING FEDERALLY
FUNDED RESEARCH OR DEVELOPMENT

This invention was made with Government Support under Contract GR526115 and GR526116 awarded by the Intelligence Advanced Research Projects Activity (IARPA). The Government has certain rights in the invention.

FIELD OF THE APPLICATION

The application relates to switching the magnetization of nanomagnets and particularly to a base element structure and method for switching the magnetization of nanomagnets.

BACKGROUND

Complementary metal-oxide-semiconductor (CMOS) technologies are prevalent today in memory and logic systems. However, CMOS technologies no longer provide a desired balance of fast operation, high density integration, and energy efficiency.

SUMMARY

According to one aspect, a base element for switching a magnetization state of a nanomagnet includes a heavy-metal strip having a surface. A ferromagnetic nanomagnet is disposed adjacent to the surface. The ferromagnetic nanomagnet has a first magnetization equilibrium state and a second magnetization equilibrium state. The first magnetization equilibrium state or the second magnetization equilibrium state is settable in an absence of an external magnetic field by a flow of electrical charge through the heavy-metal strip.

In another embodiment, the flow of electrical charge in a first direction through the heavy-metal strip causes the first magnetization equilibrium state and the flow of electrical charge in a second direction through the heavy-metal strip causes the second magnetization equilibrium state.

In yet another embodiment, the nanomagnet includes an elliptical shape having a long axis and a short axis.

In yet another embodiment, the long axis is about parallel to the surface of the heavy-metal strip.

In yet another embodiment, a direction of flow of the electrical charge through the heavy-metal strip includes an angle ξ with respect to the short axis of the nanomagnet.

In yet another embodiment, the angle ξ determines an energy of switching.

In yet another embodiment, the angle ξ determines a speed of switching.

In yet another embodiment, the base element provides a bit of an integrated memory device.

In yet another embodiment, the base element provides a bit of an integrated logic device.

In yet another embodiment, the base element provides a bit of an integrated pipelined microprocessor device.

In yet another embodiment, the heavy-metal strip includes tungsten or tantalum.

In yet another embodiment, the heavy-metal strip includes Aluminum (Al) or Gold (Au).

In yet another embodiment, the heavy-metal strip includes Bismuth (Bi) or Molybdenum (Mo).

In yet another embodiment, the heavy-metal strip includes Niobium (Nb) or Palladium (Pd).

In yet another embodiment, the heavy-metal strip includes Platinum (Pt).

In yet another embodiment, the heavy-metal strip includes an alloy of copper (Cu) and Bi, or an alloy of Cu and iridium (Ir).

According to another aspect, a method for switching a magnetization state of a nanomagnet includes the steps of: providing a heavy-metal strip having a surface and a ferromagnetic nanomagnet disposed adjacent to the surface, the ferromagnetic nanomagnet having a first magnetization equilibrium state and a second magnetization equilibrium state; flowing an electrical charge through the heavy-metal strip in an electrical charge direction to set the magnetization state of the nanomagnet in an absence of an external magnetic field to the first magnetization equilibrium state, or to set the magnetization state to the second magnetization equilibrium state.

In another embodiment, the step of flowing an electrical charge includes flowing an electrical charge through the heavy-metal strip in an electrical charge direction to set the magnetization state within a time period of less than about 50 picoseconds.

In yet another embodiment, the step of flowing an electrical charge includes flowing an electrical charge through the heavy-metal strip in an electrical charge direction to set the magnetization state where the magnetization state corresponds to setting a bit of a memory device.

In yet another embodiment, the step of flowing an electrical charge includes flowing an electrical charge through the heavy-metal strip in an electrical charge direction to set the magnetization state where the magnetization state corresponds to setting a bit of a logic device.

The foregoing and other aspects, features, and advantages of the application will become more apparent from the following description and from the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The features of the application can be better understood with reference to the drawings described below, and the claims. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles described herein. In the drawings, like numerals are used to indicate like parts throughout the various views.

FIG. 1 is a drawing showing a ferromagnetic layer adjacent to a heavy-metal nonmagnetic nanostructure;

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FIG. 2 is a drawing showing how the dynamics of the magnetization motion can be captured by ϑ and φ ;

FIG. 3A is a drawing showing that the charge current (J_e) injected through the nonmagnetic heavy-metal induces spin current (J_s);

FIG. 3B is a drawing showing an exemplary elliptical ferromagnet having an in-plane anisotropy H_{kx} ;

FIG. 3C is a drawing that shows the charge current direction and orientation of the spin polarization σ with respect to H_{kx} ;

FIG. 4 is a drawing showing the motion of magnetization under the influence of spin-torques and anisotropies; and

FIG. 5 is a drawing showing the trajectory of the magnetization switching of a ferromagnetic layer using spin-orbit torques in the absence of an external magnetic field.

DETAILED DESCRIPTION

Magnetization switching of ferromagnets using spin-orbit torques provides opportunities to introduce nanomagnets into high performance logic and memory applications requiring low power consumption. Nanomagnets with perpendicular-to-the-plane anisotropy have recently attracted a considerable attention due to their high thermal stability. High stability against thermal fluctuations allows nanomagnets to be deeply scaled down, resulting in dense logic and memory systems with ultra-low power consumption. However, due to the symmetric energy landscape experienced by the magnetization of a nanomagnet with perpendicular-to-the-plane anisotropy, spin-orbit torques induced by an in-plane current pulse cannot switch the magnetization. An external magnetic field is, therefore, required to assist spin-orbit torques by breaking the symmetry. Although the energy dissipated by switching a nanomagnet could be small, the energy necessary to generate the required magnetic field makes the overall memory or logic scheme uncompetitive as compared to complementary metal-oxide-semiconductor (CMOS) counterparts. Additional metals are also necessary to produce the required magnetic field, significantly decrease the number of devices which can be integrated over a given area. Therefore, the need for an external magnetic field is an obstacle for developing dense low power memory and logic systems. Furthermore, fast switching requires higher energy to be injected through the ferromagnet and/or metals producing magnetic field. Since the required energy grows significantly as the desired switching speed increases, fast operation compromises the energy efficiency.

A solution to the problems described hereinabove switches the magnetization of a nanomagnet with perpendicular-to-the-plane anisotropy using spin-orbit torques induced by an in-plane current pulse without the presence of an external magnetic field.

The solution includes a scheme to switch the magnetization of a nanomagnet with perpendicular-to-the-plane anisotropy using spin-orbit torques induced by an in-plane current pulse without the presence of an external magnetic field. It was realized that magnetization switching can be achieved by breaking the symmetry by introducing an in-plane anisotropy into the nanomagnet. We describe how spin orbit torques induced by an in-plane current pulse of appropriate amplitude and duration are sufficient to switch the magnetization of the nanomagnet in absence of an external magnetic field. For a given ratio between the in-plane and perpendicular-to-the-plane anisotropies, high switching probability (deterministic switching) is achievable for current pulses of significantly short duration by balancing the spin-orbit and damping torques, resulting in ultra-

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fast switching. Furthermore, since external magnetic field is not required for magnetization switching within the described scheme, energy efficiency and integration density is significantly improved, resulting in ultra-fast dense memory and low power consumption logic systems.

FIG. 1 shows an exemplary ferromagnetic layer including a perpendicular-to-the-plane anisotropy (H_{kz}) and an in-plane anisotropy (H_{kx}) is situated on a heavy-metal nanostrip. In one exemplary embodiment, the proposed structure of base element **100**, FIG. 1 shows a ferromagnetic layer represented by a Stoner-Wohlfarth monodomain magnetic body **101** with magnetization M , situated at a heavy-metal nonmagnetic nanostrip **102** with strong spin-orbit coupling. The ferromagnetic layer, as shown in FIG. 1, includes a perpendicular-to-the-plane uniaxial anisotropy H_{kz} along the e_z axis and an in-plane uniaxial anisotropy H_{kx} along the e_x axis.

FIG. 2 shows how the dynamics of the magnetization motion can be captured by ϑ and φ . As shown in FIG. 2, the motion of M is represented by a unit vector n_m , which makes an angle ϑ with e_z axis, while the plane of M and e_z makes an angle φ with e_x .

FIG. 3A shows that the charge current (J_e) injected through the nonmagnetic heavy-metal induces spin current (J_s). As shown in FIG. 3A, a charge current J_e , injected through the heavy-metal nanostrip, produces a traverse spin current $J_s = \theta_{SH}(\sigma \times J_e)$ due to the spin-orbit interaction, where J_e is the charge current density, σ is the spin polarization unit vector, and θ_{SH} is the material dependent spin Hall angle.

FIG. 3B shows an illustration of an exemplary elliptical ferromagnet having an in-plane anisotropy H_{kx} .

FIG. 3C shows the charge current direction **301** and orientation of the spin polarization σ with respect to the H_{kx} . As shown in FIG. 3C, the direction of the charge current J_e makes an angle of ξ with e_y axis. Spin polarized current transports spin angular momentum into the nanomagnet, exerting a torque on the magnetization. The dynamics of M under the influence of torques and anisotropy fields is described using the Landau-Lifshitz-Gilbert (LLG) equation as

$$\frac{dn_m}{dt} = -\gamma(n_m \times H_{eff}) + \alpha \left(n_m \times \frac{dn_m}{dt} \right) + \gamma T_{ST}, \quad (1)$$

where γ is the gyromagnetic ratio, α is the damping factor, T_{ST} is the spin torque, and H_{eff} is the effective field experienced by the magnetization of the ferromagnetic layer. H_{eff} is a function of H_{kx} and H_{kz} . The spin torque has two components, referred to as the in-plane and out-of-plane torques: $T_{ST} = T_{IP} + T_{OOP}$.

FIG. 4 shows the motion of magnetization under the influence of spin-torques and anisotropies. As demonstrated in FIG. 4, the in-plane torque T_{IP} lies in the plane defined by M and H_{eff} , and the out-of-plane torque T_{OOP} points out of the plane defined by M and H_{eff} .

FIG. 5 shows the trajectory of the magnetization switching of a ferromagnetic layer using spin-orbit torques in the absence of any external magnetic field. As shown in FIG. 5, by injecting charge current J_e through the heavy-metal nonmagnetic nanostrip, produced spin torques derive M out of the equilibrium position (also called an equilibrium state) toward the in-plane of the nanomagnet. By turning the charge current J_e off after t_e seconds, spin torque reduces to zero and M is close to the x-y plane and away from the e_z axis by an angle of ϑ . At this zone, referred here to as the

critical zone, H_{eff} is significantly dominated by H_{kx} . Therefore, M passes the hard axis by precessing around the H_{eff} . By passing the hard axis, H_{eff} is dominated by H_{kz} . Hence, M is pulled towards the new equilibrium state by precessing and damping around H_{eff} , completing the magnetization switching.

The duration t_e of the applied current pulse is as short as the time which causes the magnetization M to move from the equilibrium state to the critical zone. The magnetization switching can be performed using current pulses of a duration of sub-50 ps. Therefore, the proposed scheme significantly improves the switching speed and/or reduces the energy consumption, resulting in ultra-high-speed spin-torque memory and logic systems which have significantly low energy consumption. Furthermore, as no extra metal is required for producing an external magnetic field, integration density is considerably enhanced.

It is contemplated that both switching energy and switching speed can be determined by the angle ξ . It is also contemplated that there is a tradeoff between switching energy and switching speed as can be set by the angle ξ .

Heavy-metals as used hereinabove include any suitable transition metals having a large atomic number, such as, for example, tungsten (W), tantalum (Ta), Aluminum (Al), Gold (Au), Bismuth (Bi), Molybdenum (Mo), Niobium (Nb), Palladium (Pd), or Platinum (Pt). Also included are any suitable metal alloys, such as, for example, an alloy of copper (Cu) and Bi, or an alloy of Cu and iridium (Ir). By injecting a charge current through a heavy-metal thin film of any suitable metal or metal alloy as listed hereinabove, a traverse spin current is produced due to strong spin-orbit coupling. As described hereinabove, the produced spin current may be used to switch the direction of the magnetization of a nanomagnet. By injecting a charge current through a heavy-metal thin film, a traverse spin current is produced due to strong spin-orbit coupling. The produced spin current may be used to switch the direction of the magnetization of a nanomagnet. The magnitude of the produced spin current is directly proportional to the spin Hall angle of a thin film heavy-metal. Large spin Hall angles have been observed in some high resistivity thin films of heavy-metals. It has been shown both experimentally and theoretically that the magnitude of the spin Hall angle in some thin film heavy-metals such as, for example, thin films of W is directly proportional to the resistivity (thickness) of the thin film. For example, it has been observed that by increasing the thickness of a thin film of tungsten from 5.2 nm to 15 nm, the spin Hall angle drops from 0.33 to less than 0.07.

The magnitude of the produced spin current is directly proportional to the spin Hall angle of a thin film heavy-metal. Large spin Hall angles have been observed in some high resistivity thin films of heavy-metals. It has been shown both experimentally and theoretically that the magnitude of the measured (calculated) spin Hall angle in thin film heavy-metals is directly proportional to the resistivity (thickness) of the thin film. For example, it has been observed that by increasing the thickness of a thin film of tungsten from 5.2 nm to 15 nm, the spin Hall angle drops from 0.33 to less than 0.07.

In summary with reference to the exemplary embodiment of FIG. 1, a base element **100** for switching a magnetization state of a nanomagnet **101** includes a heavy-metal strip **102** having a surface **103**. The ferromagnetic nanomagnet **101** is disposed adjacent to the surface **103** of the heavy-metal strip **102**. The ferromagnetic nanomagnet **101** has a first magnetization equilibrium state **501** and a second magnetization equilibrium state **502** (also referred to in some embodiments

as an upward equilibrium state and a downward equilibrium state). The first magnetization equilibrium state **501** or the second magnetization equilibrium state **502** is settable by a flow of electrical charge having an electrical charge current direction **301** through the heavy-metal strip. The ferromagnetic nanomagnet can also be a feature of a magnetic layer in an integrated device incorporating the base element.

In some embodiments, by causing a flow of charge (current) in the heavy-metal strip as described hereinabove the magnetization of the nanomagnet can be switched between a first equilibrium state and a second equilibrium state, such as by reversing the direction of the flow of charge. In some contemplated applications, such as, for example where the structure is a base element of a memory or a logic system, the first equilibrium state can be assigned to either a Boolean "0" or a "1" and the second equilibrium state can be assigned to the other Boolean number different from the first equilibrium state. In such contemplated applications, the method to change the magnetization as described hereinabove is analogous to a "write" operation.

Also, in such contemplated applications, methods for reading the magnetization state of a base element are known, such as, for example, by adding an insulating layer over the nanomagnet and another magnetic layer having a fixed magnetization over the insulating layer. When the nanomagnet is switched to a magnetization equilibrium state about parallel to the magnetization of the fixed magnetization magnetic layer, there will be a low electrical resistance between the magnetic layer having a fixed magnetization and the magnetic layer having a switchable magnetization. Conversely, when the nanomagnet is switched to a magnetization equilibrium state about anti-parallel to the magnetization of the fixed magnetization magnetic layer, there will be a high electrical resistance between the magnetic layer having a fixed magnetization and the magnetic layer having a switchable magnetization. Thus, in some embodiments, a "read" operation to determine the magnetization state of the base element (e.g. a single "bit") can be performed by sensing a low resistance or a high resistance.

It is contemplated that the base element described hereinabove can be used as a bit of an integrated device, such as, for example, a memory device or a logic device. In such applications, techniques of integration known in the art can be used to form and interconnect a plurality of such base elements. It is contemplated that billions of such base elements with nanomagnets of an integrated magnetic layer can be integrated into a single integrated device. Internal integrated electrical connections between base elements can be made using integrated circuit interconnection techniques known in the art.

It will be appreciated that variants of the above-disclosed and other features and functions, or alternatives thereof, may be combined into many other different systems or applications. Various presently unforeseen or unanticipated alternatives, modifications, variations, or improvements therein may be subsequently made by those skilled in the art which are also intended to be encompassed by the following claims.

What is claimed is:

1. A base element for switching a magnetization state of a nanomagnet comprising:

a heavy-metal strip having a surface;

a ferromagnetic nanomagnet disposed adjacent to said surface, said ferromagnetic nanomagnet comprising a shape having a long axis and a short axis, said ferromagnetic nanomagnet having both a perpendicular-to-the-plane anisotropy H_{kz} and an in-plane anisotropy H_{kx}

and said ferromagnetic nanomagnet having a first magnetization equilibrium state and a second magnetization equilibrium state, said first magnetization equilibrium state or said second magnetization equilibrium state settable in an absence of an external magnetic field by a flow of electrical charge through said heavy-metal strip; and

wherein a direction of flow of said electrical charge through said heavy-metal strip comprises an angle ξ with respect to said short axis of said nanomagnet.

2. The base element of claim 1, wherein said flow of electrical charge in a first direction through said heavy-metal strip causes said first magnetization equilibrium state and said flow of electrical charge in a second direction through said heavy-metal strip causes said second magnetization equilibrium state.

3. The base element of claim 1, wherein said nanomagnet comprises an elliptical shape having a long axis and a short axis.

4. The base element of claim 3, wherein said long axis is about parallel to said surface of said heavy-metal strip.

5. The base element of claim 1, wherein said angle ξ determines an energy of switching.

6. The base element of claim 1, wherein said angle ξ determines a speed of switching.

7. The base element of claim 1, wherein said base element provides a bit of an integrated memory device.

8. The base element of claim 1, wherein said base element provides a bit of an integrated logic device.

9. The base element of claim 1, wherein said base element provides a bit of an integrated pipelined microprocessor device.

10. The base element of claim 1, wherein said heavy-metal strip comprises tungsten or tantalum.

11. The base element of claim 1, wherein said heavy-metal strip comprises Aluminum (Al) or Gold (Au).

12. The base element of claim 1, wherein said heavy-metal strip comprises Bismuth (Bi) or Molybdenum (Mo).

13. The base element of claim 1, wherein said heavy-metal strip comprises Niobium (Nb) or Palladium (Pd).

14. The base element of claim 1, wherein said heavy-metal strip comprises Platinum (Pt).

15. The base element of claim 1, wherein said heavy-metal strip comprises an alloy of copper (Cu) and Bi, or an alloy of Cu and iridium (Ir).

16. A method for switching a magnetization state of a nanomagnet comprising the steps of:
 providing a heavy-metal strip having a surface and a ferromagnetic nanomagnet disposed adjacent to said surface, said ferromagnetic nanomagnet comprising a shape having a long axis and a short axis, said ferromagnetic nanomagnet having both a perpendicular-to-the-plane anisotropy H_{kz} and an in-plane anisotropy H_{kx} , and said ferromagnetic nanomagnet having a first

magnetization equilibrium state and a second magnetization equilibrium state, and wherein a direction of flow of said electrical charge through said heavy-metal strip comprises an angle ξ with respect to said short axis of said nanomagnet; and

flowing an electrical charge through said heavy-metal strip in an electrical charge direction to set said magnetization state of said nanomagnet in an absence of an external magnetic field to said first magnetization equilibrium state, or to set said magnetization state to said second magnetization equilibrium state.

17. The method of claim 16, wherein said step of flowing an electrical charge comprises flowing an electrical charge through said heavy-metal strip in an electrical charge direction to set said magnetization state within a time period of less than about 50 picoseconds.

18. The method of claim 16, wherein said step of flowing an electrical charge comprises flowing an electrical charge through said heavy-metal strip in an electrical charge direction to set said magnetization state where said magnetization state corresponds to setting a bit of a memory device.

19. The method of claim 16, wherein said step of flowing an electrical charge comprises flowing an electrical charge through said heavy-metal strip in an electrical charge direction to set said magnetization state where said magnetization state corresponds to setting a bit of a logic device.

20. A method of controlling a trajectory of a perpendicular magnetization switching of a ferromagnetic layer using spin-orbit torques in the absence of any external magnetic field comprising:
 injecting a charge current J_e through a heavy-metal non-magnetic nanostrip disposed adjacent to a ferromagnetic layer to produce spin torques which drive a magnetization M out of an equilibrium state towards an in-plane of a nanomagnet;
 turning said charge current J_e off after t_e seconds, causing a spin torque to reduce to substantially zero where M is close to an x-y plane and away from an e_z axis by an angle of ϑ in a critical zone, where an effective field experienced by the magnetization of the ferromagnetic layer H_{eff} is significantly dominated by and in-plane anisotropy H_{kx} , and where M passes a hard axis by precessing around said H_{eff} ; and
 passing the hard axis, where H_{eff} is dominated by a perpendicular-to-the-plane anisotropy H_{kz} , and where M is pulled towards the new equilibrium state by precessing and damping around H_{eff} , completing a magnetization switching.

21. The method of claim 20, wherein said step of turning said charge current J_e off after t_e seconds comprises turning said charge current J_e off after time period of less than about 50 picoseconds.

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