(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) **World Intellectual Property Organization**
International Bureau

(43) **International Publication Date**
28 December 2017 (28.12.2017)

(10) **International Publication Number**
WO 2017/222588 A1

(51) **International Patent Classification:**
H03B 15/00 (2006.01) ***H01F 10/32*** (2006.01)

(21) **International Application Number:**
PCT/US2016/065393

(22) **International Filing Date:**
07 December 2016 (07.12.2016)

(25) **Filing Language:** English

(26) **Publication Language:** English

(30) **Priority Data:**
62/352,937 21 June 2016 (21.06.2016) US

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(81) **Designated States** *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) **Designated States** *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:
— *of inventorship (Rule 4.17(iv))*

Published:
— *with international search report (Art. 21(3))*

(54) **Title:** IN-PLANE CURRENT DRIVEN MAGNETIC SKYRMION SPIN OSCILLATOR

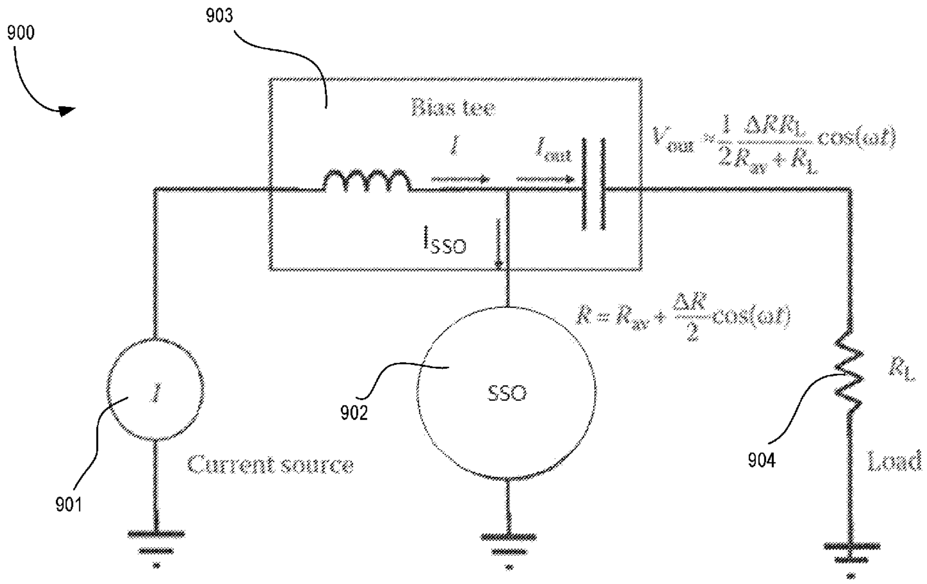

Fig. 9

(57) **Abstract:** An apparatus is provided which comprises: a current source; a bias tee having a first terminal coupled to the current source; a skyrmion spin oscillator (SSO) coupled to a second terminal of the bias tee; and a load coupled to a third terminal of the bias tee.

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IN-PLANE CURRENT DRIVEN MAGNETIC SKYRMION SPIN OSCILLATOR

CLAIM OF PRIORITY

[0001] This application claims priority of United States Provisional Application Serial No. 62/352,937 filed June 21, 2016, and is incorporated by reference in its entirety.

BACKGROUND

[0002] Magnetic Skyrmions are topological objects with distinctive magnetic properties. Magnetic Skyrmions are classified by their integer-quantized winding number 'W' which represents the number of times the field configuration covers an entire unit sphere. Oscillators are building blocks of a communication systems. However, oscillators consume high power.

BRIEF DESCRIPTION OF THE DRAWINGS

[0003] The embodiments of the disclosure will be understood more fully from the detailed description given below and from the accompanying drawings of various embodiments of the disclosure, which, however, should not be taken to limit the disclosure to the specific embodiments, but are for explanation and understanding only.

[0004] **Fig. 1** illustrates a Hedgehog Skyrmion with W=1.

[0005] **Fig. 2** illustrates a Chiral Skyrmion of combed Skyrmion with W=2.

[0006] **Fig. 3A** illustrates a three-dimensional (3D) side view of a doubly twisted field configuration about the Skyrmion center for the W=2 Skyrmion shown in **Fig. 2**.

[0007] **Fig. 3B** illustrates a top view of the doubly twisted field configuration about the Skyrmion center for the W=2 Skyrmion shown in **Fig. 3A**.

[0008] **Fig. 4** illustrates a schematic spin structure of Skyrmion lattice in a plane which produces a magnetic field perpendicular to the plane of the MnSi, in accordance with some embodiments.

[0009] **Fig. 5** illustrates a Skyrmionic Crystal ground state in FeGe.

[0010] **Fig. 6** illustrates a regular Skyrmionic crystal in $Fe_{0.5}Co_{0.5}Si$.

[0011] **Fig. 7** illustrates an arrangement of multiple Skyrmions in the Skyrmionic lattice of **Fig. 4**.

[0012] **Fig. 8** illustrates a thin film of $Fe_{0.5}Co_{0.5}$ which is deposited on a Si substrate, according to some embodiments.

[0013] **Fig. 9** illustrates a Skyrmion spin oscillator (SSO) device which functions as a reactive load that presents a frequency dependent complex impedance in a simple voltage circuit, according to some embodiments of the disclosure.

[0014] **Fig. 10** illustrates a method flowchart for forming a Skyrmion Spin Resonator device, according to some embodiments of the disclosure.

[0015] **Fig. 11** illustrates a method flowchart for forming a Skyrmion spin oscillator device, according to some embodiments of the disclosure.

[0016] **Fig. 12** illustrates a smart device or a computer system or a SoC (System-on-Chip) with a Skyrmion Spin Resonator device and/or Skyrmion spin oscillator device, according to some embodiments of the disclosure.

DETAILED DESCRIPTION

[0017] **Fig. 1** illustrates a Hedgehog Skyrmion 100 with W=1. **Fig. 2** illustrates a Chiral Skyrmion 200 or combed Skyrmion with W=2. **Fig. 3A** illustrates a three-dimensional (3D) side view 300 of a doubly twisted field configuration (e.g., fields 301, 302, 303, 304, and 305) about the Skyrmion center for the W=2 Skyrmion shown in **Fig. 2**. **Fig. 3B** illustrates a top view 320 of the doubly twisted field configuration about the Skyrmion center for the W=2 Skyrmion shown in **Fig. 3A**.

[0018] Magnetic Skyrmions have been both theoretically predicted and experimentally observed in condensed matter systems with topological protection. The topological properties of magnetic Skyrmions derive from the fact that their internal magnetic field configuration cannot be continuously deformed into a collinear configuration in which they are embedded and which is common in most ferromagnetic material systems. The topological isolation of magnetic Skyrmion allows them to be treated as magnetic quasiparticles and be moved, manipulated, created, and destroyed. Magnetic Skyrmions are also topologically protected. For example, magnetic Skyrmions are much less likely to become pinned to defects in the host material. Additionally, the interaction of magnetic Skyrmions with externally applied fields and currents is highly efficient compared to conventional devices because of the Emergent Electromagnetic Field (EEMF).

[0019] The EEMF is a very strong force that exists between conduction electrons and local magnetic spin textures and has been observed in many thin film material systems with out-of-plane magnetic fields. It results from an interplay of the Coulomb potential and the Pauli Exclusion Principle that results from a free electron interacting with a bound electron. It is the same effect responsible for the filling sequence of atomic shells defined by the

Hund's rule. In magnetic substrates, the EEMF is directly proportional to the field gradients associated with the equilibrium magnetic texture in the host materials. Because of the confined structure of the Skyrmions, the local field gradients can be as high as 11 Tesla (T) in MnSi based systems, for example. This results in very efficient momentum coupling between the conduction electrons and Skyrmions.

[0020] A characteristic of current flow in a topological insulator is that the spin vector is locked to the momentum vector. This results in a much stronger spin transfer effect than observed in bulk materials. Spin orbit interactions in heavy-metal/ferromagnet bilayers can produce strong current-driven torques on the magnetic layer, via the spin Hall effect in the heavy metal or the Rashba–Edelstein effect in the ferromagnet. Topological insulators, which possess a surface state in which the effects of spin orbit coupling are maximal in the sense that an electron's spin orientation is fixed relative to its propagation direction can provide even more efficient spin orbit induced torque.

[0021] Various embodiments describe oscillators and resonators comprising magnetic Skyrmions. These oscillators and resonators can be organized in arrays. In some embodiments, the magnetic Skyrmions are driven by in-plane currents flowing in a thin film ferromagnetic material in which the Skyrmions are embedded. Here, the torque transfer process is very efficient due to the EEMF which exists between conduction electrons and high gradient magnetic fields such as those existing internal to the Skyrmion.

[0022] These oscillators of various embodiments can generate high frequency (e.g., 100 Giga Hertz (GHz) to 1000 GHz) output using a very small area (e.g., 10 to 100 nanometers (nm)). As such, the Skyrmion oscillators of various embodiments are efficient. The magnetic Skyrmion based oscillators of various embodiments are more efficient than the spin torque transfer (STT) produced by either the Slonczewski interaction or spin Hall interaction measured in terms of radio frequency (RF) power-out over Direct Current (DC) power-in. The magnetic Skyrmion based oscillators of various embodiments are also more compact than existing spin torque oscillators and can be laid out in a two-dimensional (2D) configuration as opposed to a three-dimensional (3D) configuration with out-of-plane current drive.

[0023] In the following description, numerous details are discussed to provide a more thorough explanation of embodiments of the present disclosure. It will be apparent, however, to one skilled in the art, that embodiments of the present disclosure may be practiced without these specific details. In other instances, well-known structures and devices are shown in block diagram form, rather than in detail, in order to avoid obscuring embodiments of the present disclosure.

[0024] Note that in the corresponding drawings of the embodiments, signals are represented with lines. Some lines may be thicker, to indicate more constituent signal paths, and/or have arrows at one or more ends, to indicate primary information flow direction. Such indications are not intended to be limiting. Rather, the lines are used in connection with one or more exemplary embodiments to facilitate easier understanding of a circuit or a logical unit. Any represented signal, as dictated by design needs or preferences, may actually comprise one or more signals that may travel in either direction and may be implemented with any suitable type of signal scheme.

[0025] Throughout the specification, and in the claims, the term "connected" means a direct physical, electrical, or wireless connection between the things that are connected, without any intermediary devices. The term "coupled" means either a direct electrical or wireless connection between the things that are connected or an indirect electrical or wireless connection through one or more passive or active intermediary devices. The term "circuit" means one or more passive and/or active components that are arranged to cooperate with one another to provide a desired function. The term "signal" means at least one current signal, voltage signal, magnetic signal, electromagnetic signal, or data/clock signal. The meaning of "a," "an," and "the" include plural references. The meaning of "in" includes "in" and "on."

[0026] The terms “substantially,” “close,” “approximately,” “near,” and “about,” generally refer to being within +/- 10% of a target value (unless specifically specified). Unless otherwise specified the use of the ordinal adjectives “first,” “second,” and “third,” etc., to describe a common object, merely indicate that different instances of like objects are being referred to, and are not intended to imply that the objects so described must be in a given sequence, either temporally, spatially, in ranking or in any other manner.

[0027] Unless otherwise specified the use of the ordinal adjectives “first,” “second,” and “third,” etc., to describe a common object, merely indicate that different instances of like objects are being referred to, and are not intended to imply that the objects so described must be in a given sequence, either temporally, spatially, in ranking or in any other manner.

[0028] For the purposes of the present disclosure, phrases “A and/or B” and “A or B” mean (A), (B), or (A and B). For the purposes of the present disclosure, the phrase “A, B, and/or C” means (A), (B), (C), (A and B), (A and C), (B and C), or (A, B and C). The terms “left,” “right,” “front,” “back,” “top,” “bottom,” “over,” “under,” and the like in the description and in the claims, if any, are used for descriptive purposes and not necessarily for describing permanent relative positions.

[0029] **Fig. 4** illustrates a schematic spin structure of Skyrmion lattice 400 in a plane which produces a magnetic field perpendicular to the plane of the MnSi, in accordance with some embodiments.

[0030] In some embodiments, charge current flowing in-plane in a thin film of a topological insulator at room temperature can exert a strong spin-transfer torque on an adjacent ferromagnetic permalloy thin film, with a direction consistent with that expected from the topological surface state. Here, perpendicular component of the magnetic field is indicated by 401 while the in-plane components of the magnetic field are indicated by 402. In some embodiments, the thin film of a topological insulator comprises Bi and Si (e.g., Bi_2Se_3). In other embodiments, other material(s) may be used for the topological insulator. For example, topological insulator may comprise Fe, Co and Si (e.g., FeCoSi). In some embodiments, the ferromagnetic permalloy comprises Ni and Fe (e.g., $Ni_{81}Fe_{19}$ and other stoichiometric ratios, for instance, Ni_8Fe_{20}). In some embodiments, the strength of the torque per unit charge current density in Bi_2Si_3 is greater than for any source of spin-transfer torque measured so far, even for non-ideal topological insulator films in which the surface states coexist with bulk conduction. In some embodiments, topological insulators enable very efficient electrical manipulation of magnetic materials at room temperature, for memory and logic applications.

[0031] Skyrmion lattices in chiral magnets represent a special class of topological insulators that are attractive for Spin Torque Effects. Skyrmion lattices in chiral magnets are attractive for spin torque effects, because they are coupled very weakly to the atomic crystal structure and may be expected to pin very weakly to disorder.

[0032] Electric currents are known to couple very efficiently to Skyrmions as follows. When the conduction electrons in a metal move across a magnetic texture, their spin follows the local magnetization adiabatically. Spins that change their orientation pick up a quantum mechanical phase, the Berry phase, which may be viewed as an Aharonov-Bohm phase arising from an effective field (the Emergent Field) B^i_{eff}.

[0033] **Fig. 5** illustrates a Skyrmionic Crystal ground state 500 in FeGe which forms very regular Skyrmionic crystal structures. For example, ground state Skyrmionic crystals are observed in FeGe thin film structures of **Fig. 5**. The Skyrmions spontaneously arrange themselves into precise crystalline structures without the need for advanced patterning technologies (e.g., with inter Skyrmion spacing of approximately 12 nanometers (nm)). It forms the ground state (e.g., the lowest energy state) of the thin film material system.

[0034] In some embodiments, the close proximity and regular spacing in the crystalline structures allow the EEMF fields to produce very efficient coupling between an applied current and Skyrmion structures. In some embodiments, and at some wavelengths, the individual Skyrmions couple coherently and efficiently to nearby Skyrmions multiplying in power produced by an individual Skyrmion. Such systems provide the functionality required to implement highly efficient microwave generators, precise microwave filters, and associative processors based on synchronization dynamics, in accordance with some embodiments.

[0035] Various embodiments use magnetic Skyrmion arrays as oscillators. In some embodiments, the Skyrmions are driven by in-plane currents flowing in a thin film ferromagnetic material in which the Skyrmions are embedded. The torque transfer process is extremely efficient due to the EEMF which exists between conduction electrons and high gradient magnetic fields such as those existing internal to the Skyrmion.

[0036] Current induced coupling to Skyrmions is more efficient than the spin torque transfer produced by either the Slonczewski interaction or the Spin Hall interaction measured in terms of RF power-out over DC power-in. Skyrmions are also more compact than existing spin torque oscillators and can be laid out in a 2D configuration as opposed to 3D configuration with out-of-plane current drive of an existing art.

[0037] The Skyrmion Spin Oscillator (SSO) described here with reference to the various embodiments is one instantiation of a broad class of devices which are based on the EEMF. The EEMF interaction is 10^2 to10^3 times stronger than that of the coupling currently used in existing spintronic devices. EEMF interaction results from the ordering induced by the high magnetic field gradients present in magnetic Skyrmions and other confined magnetic textures (e.g., **Fig. 5**). The strength of that interaction opens the door for potentially radically new devices including but not limited to the SSO.

[0038] In some embodiments, the SSO is a nonlinear dynamic system embedded in a suitable material system that has a stable limit cycle and undergoes high frequency oscillation at RF frequencies when driven by uniform DC (Direct Current) current.

[0039] The SSO of various embodiments is differentiated from Spin torque Oscillators (STO) and Spin Hall effect oscillators (SHO) by the mechanism which couples the moving conduction electrons to the magnetic texture in the material system. The mechanism used by SSOs is the EEMF, in accordance with some embodiments. That EEMF is at least 10^3 times stronger than the Spin Transfer Torque observed in bulk ferromagnetic materials. The EEMF is also at least 10^2 time stronger than the Rashba coupling observed in Spin Hall Oscillators.

[0040] In some embodiments, an extremely large magnitude of the EEMF is applied at the edge of isolated Skyrmions to yield extremely large torques relative to other spin oscillator implementations. As such energy efficient oscillators operating in frequency regimes of great technological interest are implemented.

[0041] In some embodiments, the SSOs are topologically protected systems which make them robust to defects and imperfections in the material substrates. The magnetic Skyrmions are strongly confined dimensionally with diameters ranging from 10 nm to 1000 nm. As such, ultra-dense microwave generators are realized in accordance with some embodiments operating at 100 to 1000 GHz (Giga Hertz) and also coupled oscillator arrays suitable for Convolutional Neural Networks (CNNs). SSOs and SSO crystals of various embodiments have great application potential for ultra-dense and efficient microwave power sources, very precise frequency filters, convolutional engines, neuromorphic processors, and associative processors, for example.

[0042] The SSO of various embodiments can be used as the basic RF power source required for any form of mobile, handheld, embedded or wearable device (e.g., the basic RF power source for any edge node needed for the Internet-of-Things (IoT)).

[0043] In some embodiments, a 2D locally confined array of magnetic Skyrmions is formed in a thin film topologically protected ferromagnetic material. Under suitable magnetic conditions, the Skyrmions arrange themselves into a regular crystal lattice structure with a regular lattice spacing and regular magnetic texture inside each Skyrmion.

[0044] **Fig. 6** illustrates a regular Skyrmionic crystal 600 in $Fe_{0.5}Co_{0.5}Si$. The close proximity of the Skyrmions (e.g., especially at their circumference) results in close coupling of their rotational modes. For instance, a rotation in one Skyrmion will induce rotations in adjacent Skyrmions. **Fig. 7** shows inside detail of the chiral magnetic structure 700. The map and arrows in the chiral magnetic structure 700 show the magnetic field direction at each point in the crystal.

[0045] **Fig. 8** illustrates an apparatus 800 having a thin film of ferromagnetic material (e.g., $Fe_{0.5}Co_{0.5}$) which is deposited on a substrate (e.g., Si), according to some embodiments. In some embodiments, apparatus 800 comprises thin film of ferromagnetic material 801 having a skyrmionic lattice, metal contacts 802a and 802b, and an Alternating Current (AC) source 803. In some embodiments, an AC voltage is applied to the ferromagnetic thin film

801 causing a current to flow between contacts 802a/b (e.g., non-magnetic metals) in the plane of the topologically protected thin film.

[0046] Apparatus 800 forms a component of a basic oscillator, which is referred to as Skyrmion Spin Resonator. Note, an oscillator generally includes a gain element. In some embodiments, the current paths internal to the Skyrmion Spin Resonator follows the paths of least resistance which lie in the areas where the magnetic field is confined to the plane of the substrate. This is due to the fact that the spin vector is aligned with the momentum vector in a topologically insulating material. It is also due to the fact that in the region between Skyrmions, the magtnetic field lies in-plane and Anisotropic Magneto Resistance will be smallest when the electron spin vector is aligned with the magnetic fields in the sample.

[0047] In some embodiments, the fraction of conduction electrons flowing at the boundaries of the Skyrmions in material 801 exert a torque on each of the Skyrmions and excite rotation of individual Skyrmions or small clusters of Skyrmions. The efficiency of Skyrmion excitation by conduction electrons is expected to be much stronger than other forms of coupling (spin Hall coupling or Slonczewki spin torque) due to the presence of the Emergent Electromagnetic Fields as explained in the background section.

[0048] **Fig. 9** illustrates a Skyrmion spin oscillator (SSO) device 900 which functions as a reactive load that presents a frequency dependent complex impedance in a simple voltage circuit, according to some embodiments of the disclosure. In some embodiments, SSO device 900 comprises current source 901, SSO 902, bias tee 903, and load 904. In some embodiments, current source 901 provides an excitation current *I* to SSO 902 via bias tee 903. In some embodiments, SSO 902 is formed of $Fe_{0.5}Co_{0.5}Si$. In other embodiments, topologically insulated materials with stable Skyrmion phase state such as MnSi, FeGe, $Co_9Zn_9Mn_2$, $Co_{10}Zn_{10}$, $La_3Mn_2O_7$, or $Sr_3Mn_2O_7$ may be used for forming SSO 902.

[0049] Bias Tee 903 is a three-port network (also known as a diplexer) that provdes a DC bias point for SSO 902, in accordance with some embodiments. The low frequency port of bias tee 903 is coupled to current source 901 while the high-frequency port is coupled to load 904. For sake of not obscuring the various embodiments, here load 904 is modeled as a resistor. Load 904 can be any circuit that needs an oscillating input. The SSO device 900 of various embodiments functions as a reactive load that presents a frequency dependent complex impedance. The output voltage at the Skyrmion oscillation frequency appear across the load resistance R_L, in accordacne with some embodiments.

[0050] **Fig. 10** illustrates a method flowchart 1000 for forming a Skyrmion Spin Resonator device, according to some embodiments of the disclosure. It is pointed out that those elements of **Fig. 10** having the same reference numbers (or names) as the elements of any other figure can operate or function in any manner similar to that described, but are not limited to such.

[0051] At block 1001, a first contact (e.g., 802a) is formed. At block 1002, a second contact (e.g., 802b) is formed. In some embodiments, the first and second contacts comprise non-magnetic metals (e.g., Cu, Ag. Au, etc.). At block 1003, a layer (e.g., 801) comprising Skyrmions is formed which is coupled to the first and second contacts. In some embodiments, the layer comprising Skyrmions comprises a material selected from a group consisting of: $Fe_{0.5}Co_{0.5}Si$, MnSi, FeGe, $Co_9Zn_9Mn_2$, $Co_{10}Zn_{10}$, $La_3Mn_2O_7$, and $Sr_3Mn_2O_7$. In some embodiments, the layer comprising Skyrmions comprises of a material selected from a group consisting of: Fe, Co, Si, Mn, La, Zn, and Sr. At block 1004, a voltage source is coupled to the first and second contacts (803a/b). In some embodiments, the voltage source is an Alternating Current (AC) voltage source.

[0052] **Fig. 11** illustrates a method flowchart 1100 for forming a Skyrmion spin oscillator device, according to some embodiments of the disclosure. It is pointed out that those elements of **Fig. 11** having the same reference numbers (or names) as the elements of any other figure can operate or function in any manner similar to that described, but are not limited to such.

[0053] At block 1101, a current source (e.g., 901) is provided. At block 1102, a first terminal of a bias tee (e.g., 903) is coupled to the current source. At block 1103, a Skyrmion spin oscillator (SSO) (e.g., 902) is formed. In some embodiments, the SSO comprises a material selected from a group consisting of: $Fe_{0.5}Co_{0.5}Si$, MnSi, FeGe, $Co_9Zn_9Mn_2$, $Co_{10}Zn_{10}$,$La_3Mn_2O_7$, and $Sr_3Mn_2O_7$. In some embodiments, the SSO 902 comprises of a material selected from a group consisting of: Fe, Co, Si, Mn, La, Zn, and Sr. At block 1104, the SSO 902 is coupled to a second terminal of the bias tee 903. At block 1105, an oscillating signal from the SSO 902 is provided to a load (e.g., 904) coupled to a third terminal of the bias tee 903.

[0054] Although the blocks in the flowchart with reference to **Figs. 10-11** are shown in a particular order, the order of the actions can be modified. Thus, the illustrated embodiments can be performed in a different order, and some actions/blocks may be performed in parallel. Some of the blocks and/or operations listed in **Figs. 10-11** are optional in accordance with certain embodiments. The numbering of the blocks presented is for the sake of clarity and is not intended to prescribe an order of operations in which the various blocks must occur. Additionally, operations from the various flows may be utilized in a variety of combinations.

[0055] **Fig. 12** illustrates a smart device or a computer system or a SoC (System-on-Chip) with a Skyrmion spin oscillator or Skyrmion Spin Resonator according to some embodiments of the disclosure. It is pointed out that those elements of **Fig. 12** having the same reference numbers (or names) as the elements of any other figure can operate or function in any manner similar to that described, but are not limited to such.

[0056] **Fig. 12** illustrates a block diagram of an embodiment of a mobile device in which flat surface interface connectors could be used. In some embodiments, computing device 1600 represents a mobile computing device, such as a computing tablet, a mobile phone or smart-phone, a wireless-enabled e-reader, or other wireless mobile device. It will be understood that certain components are shown generally, and not all components of such a device are shown in computing device 1600.

[0057] For purposes of the embodiments, the transistors in various circuits and logic blocks described here are metal oxide semiconductor (MOS) transistors, which include drain, source, gate, and bulk terminals. The transistors also include Tri-Gate and FinFET transistors, Gate All Around Cylindrical Transistors, Tunneling FET (TFET), Square Wire, or Rectangular Ribbon Transistors or other devices implementing transistor functionality like carbon nanotubes or spintronic devices. MOSFET symmetrical source and drain terminals i.e., are identical terminals and are interchangeably used here. A TFET device, on the other hand, has asymmetric Source and Drain terminals. Those skilled in the art will appreciate that other transistors, for example, Bi-polar junction transistors—BJT PNP/NPN, BiCMOS, CMOS, eFET, etc., may be used without departing from the scope of the disclosure.

[0058] In some embodiments, computing device 1600 includes first processor 1610 with a Skyrmion spin oscillator or Skyrmion Spin Resonator, according to some embodiments discussed. Other blocks of the computing device 1600 may also include a Skyrmion spin oscillator or Skyrmion Spin Resonator, according to some embodiments. The various embodiments of the present disclosure may also comprise a network interface within 1670 such as a wireless interface so that a system embodiment may be incorporated into a wireless device, for example, cell phone or personal digital assistant.

[0059] In some embodiments, processor 1610 can include one or more physical devices, such as microprocessors, application processors, microcontrollers, programmable logic devices, or other processing means. The processing operations performed by processor 1610 include the execution of an operating platform or operating system on which applications and/or device functions are executed. The processing operations include operations related to I/O (input/output) with a human user or with other devices, operations related to power management, and/or operations related to connecting the computing device 1600 to another device. The processing operations may also include operations related to audio I/O and/or display I/O.

[0060] In some embodiments, computing device 1600 includes audio subsystem 1620, which represents hardware (e.g., audio hardware and audio circuits) and software (e.g., drivers, codecs) components associated with providing audio functions to the computing device. Audio functions can include speaker and/or headphone output, as well as microphone input. Devices for such functions can be integrated into computing device 1600, or connected to the computing device 1600. In one embodiment, a user interacts with the computing device 1600 by providing audio commands that are received and processed by processor 1610.

[0061] In some embodiments, computing device 1600 comprises display subsystem 1630. Display subsystem 1630 represents hardware (e.g., display devices) and software (e.g., drivers) components that provide a visual and/or tactile display for a user to interact with the computing device 1600. Display subsystem 1630 includes display interface 1632, which includes the particular screen or hardware device used to provide a display to a user. In one embodiment, display interface 1632 includes logic separate from processor 1610 to perform at least some processing related to the display. In one embodiment, display subsystem 1630 includes a touch screen (or touch pad) device that provides both output and input to a user.

[0062] In some embodiments, computing device 1600 comprises I/O controller 1640. I/O controller 1640 represents hardware devices and software components related to interaction with a user. I/O controller 1640 is operable to manage hardware that is part of audio subsystem 1620 and/or display subsystem 1630. Additionally, I/O controller 1640 illustrates a connection point for additional devices that connect to computing device 1600 through which a user might interact with the system. For example, devices that can be attached to the computing device 1600 might include microphone devices, speaker or stereo systems, video systems or other display devices, keyboard or keypad devices, or other I/O devices for use with specific applications such as card readers or other devices.

[0063] As mentioned above, I/O controller 1640 can interact with audio subsystem 1620 and/or display subsystem 1630. For example, input through a microphone or other audio device can provide input or commands for one or more applications or functions of the computing device 1600. Additionally, audio output can be provided instead of, or in addition to display output. In another example, if display subsystem 1630 includes a touch screen, the display device also acts as an input device, which can be at least partially managed by I/O controller 1640. There can also be additional buttons or switches on the computing device 1600 to provide I/O functions managed by I/O controller 1640.

[0064] In some embodiments, I/O controller 1640 manages devices such as accelerometers, cameras, light sensors or other environmental sensors, or other hardware that can be included in the computing device 1600. The input can be part of direct user interaction, as well as providing environmental input to the system to influence its operations (such as filtering for noise, adjusting displays for brightness detection, applying a flash for a camera, or other features).

[0065] In some embodiments, computing device 1600 includes power management 1650 that manages battery power usage, charging of the battery, and features related to power saving operation. Memory subsystem 1660 includes memory devices for storing information in computing device 1600. Memory can include nonvolatile (state does not change if power to the memory device is interrupted) and/or volatile (state is indeterminate if power to the memory device is interrupted) memory devices. Memory subsystem 1660 can store application data, user data, music, photos, documents, or other data, as well as system data (whether long-term or temporary) related to the execution of the applications and functions of the computing device 1600.

[0066] Elements of embodiments are also provided as a machine-readable medium (e.g., memory 1660) for storing the computer-executable instructions (e.g., instructions to implement any other processes discussed herein). The machine-readable medium (e.g., memory 1660) may include, but is not limited to, flash memory, optical disks, CD-ROMs, DVD ROMs, RAMs, EPROMs, EEPROMs, magnetic or optical cards, phase change memory (PCM), or other types of machine-readable media suitable for storing electronic or computer-executable instructions. For example, embodiments of the disclosure may be downloaded as a computer program (e.g., BIOS) which may be transferred from a remote computer (e.g., a server) to a requesting computer (e.g., a client) by way of data signals via a communication link (e.g., a modem or network connection).

[0067] In some embodiments, computing device 1600 comprises connectivity 1670. Connectivity 1670 includes hardware devices (e.g., wireless and/or wired connectors and communication hardware) and software components (e.g., drivers, protocol stacks) to enable the computing device 1600 to communicate with external devices. The computing device

1600 could be separate devices, such as other computing devices, wireless access points or base stations, as well as peripherals such as headsets, printers, or other devices.

[0068] Connectivity 1670 can include multiple different types of connectivity. To generalize, the computing device 1600 is illustrated with cellular connectivity 1672 and wireless connectivity 1674. Cellular connectivity 1672 refers generally to cellular network connectivity provided by wireless carriers, such as provided via GSM (global system for mobile communications) or variations or derivatives, CDMA (code division multiple access) or variations or derivatives, TDM (time division multiplexing) or variations or derivatives, or other cellular service standards. Wireless connectivity (or wireless interface) 1674 refers to wireless connectivity that is not cellular, and can include personal area networks (such as Bluetooth, Near Field, etc.), local area networks (such as Wi-Fi), and/or wide area networks (such as WiMax), or other wireless communication.

[0069] In some embodiments, computing device 1600 comprises peripheral connections 1680. Peripheral connections 1680 include hardware interfaces and connectors, as well as software components (e.g., drivers, protocol stacks) to make peripheral connections. It will be understood that the computing device 1600 could both be a peripheral device ("to" 1682) to other computing devices, as well as have peripheral devices ("from" 1684) connected to it. The computing device 1600 commonly has a "docking" connector to connect to other computing devices for purposes such as managing (e.g., downloading and/or uploading, changing, synchronizing) content on computing device 1600. Additionally, a docking connector can allow computing device 1600 to connect to certain peripherals that allow the computing device 1600 to control content output, for example, to audiovisual or other systems.

[0070] In addition to a proprietary docking connector or other proprietary connection hardware, the computing device 1600 can make peripheral connections 1680 via common or standards-based connectors. Common types can include a Universal Serial Bus (USB) connector (which can include any of a number of different hardware interfaces), DisplayPort including MiniDisplayPort (MDP), High Definition Multimedia Interface (HDMI), Firewire, or other types.

[0071] Reference in the specification to "an embodiment," "one embodiment," "some embodiments," or "other embodiments" means that a particular feature, structure, or characteristic described in connection with the embodiments is included in at least some embodiments, but not necessarily all embodiments. The various appearances of "an embodiment," "one embodiment," or "some embodiments" are not necessarily all referring to the same embodiments. If the specification states a component, feature, structure, or characteristic "may," "might," or "could" be included, that particular component, feature, structure, or characteristic is not required to be included. If the specification or claim refers to "a" or "an" element, that does not mean there is only one of the elements. If the specification or claims refer to "an additional" element, that does not preclude there being more than one of the additional element.

[0072] Furthermore, the particular features, structures, functions, or characteristics may be combined in any suitable manner in one or more embodiments. For example, a first embodiment may be combined with a second embodiment anywhere the particular features, structures, functions, or characteristics associated with the two embodiments are not mutually exclusive.

[0073] The following examples pertain to further embodiments. Specifics in the examples may be used anywhere in one or more embodiments. All optional features of the apparatus described herein may also be implemented with respect to a method or process. The embodiments described here can be combined with other embodiments described herein without changing the essence of the invention(s) of this disclosure.

[0074] For example, an apparatus is provided which comprises: a first contact; a second contact; a layer comprising Skyrmions coupled to the first and second contacts; and a voltage source coupled to the first and second contacts. In some embodiments, the layer comprising Skyrmions includes a material comprising one or more of: $Fe_{0.5}Co_{0.5}Si$, MnSi, FeGe, $Co_9Zn_9Mn_2$, $Co_{10}Zn_{10}$, $La_3Mn_2O_7$, or $Sr_3Mn_2O_7$. In some embodiments, the layer comprising Skyrmions includes a material comprising one or more of: Fe, Co, Si, Mn, Ge, O, La, Zn, or Sr. In some embodiments, the first and second contacts comprise non-magnetic metals. In some embodiments, the voltage source is an Alternating Current (AC) voltage source.

[0075] In another example, a system is provided which comprises: a memory; a processor coupled to the memory, the processor including an apparatus according to the apparatus described above; and a wireless interface for allowing the processor to communicate with another device.

[0076] In another example, an apparatus is provided which comprises: a current source; a bias tee having a first terminal coupled to the current source; a skyrmion spin oscillator (SSO) coupled to a second terminal of the bias tee; and a load coupled to a third terminal of the bias tee. In some embodiments, the SSO comprises a material which includes one or more of: $Fe_{0.5}Co_{0.5}Si$, MnSi, FeGe, $Co_9Zn_9Mn_2$, $Co_{10}Zn_{10}$, $La_3Mn_2O_7$, or $Sr_3Mn_2O_7$. In some embodiments, the SSO includes a material comprising one or more of: Fe, Co, Si, Mn, Ge, O, La, Zn, or Sr.

[0077] In another example, a system is provided which comprises: a memory; a processor coupled to the memory, the processor including an apparatus according to the apparatus described above; and a wireless interface for allowing the processor to communicate with another device.

[0078] In another example, a method is provided which comprises: forming a first contact; forming a second contact; forming a layer comprising Skyrmions coupled to the first and second contacts; and coupling a voltage source to the first and second contacts. In some embodiments, the layer comprising Skyrmions includes a material comprising one or more of: $Fe_{0.5}Co_{0.5}Si$, MnSi, FeGe, $Co_9Zn_9Mn_2$, $Co_{10}Zn_{10}$, $La_3Mn_2O_7$, or $Sr_3Mn_2O_7$. In some embodiments, the layer comprising Skyrmions includes a material comprising one or more of: Fe, Co, Si, Mn, Ge, O, La, Zn, or Sr. In some embodiments, the first and second contacts comprise non-magnetic metals. In some embodiments, the voltage source is an Alternating Current (AC) voltage source.

[0079] In another example, an apparatus is provided which comprises: means for forming a first contact; means for forming a second contact; means for forming a layer comprising Skyrmions coupled to the first and second contacts; and means for coupling a voltage source to the first and second contacts. In some embodiments, the layer comprising Skyrmions includes a material comprising one or more of: $Fe_{0.5}Co_{0.5}Si$, MnSi, FeGe, $Co_9Zn_9Mn_2$, $Co_{10}Zn_{10}$, $La_3Mn_2O_7$, or $Sr_3Mn_2O_7$. In some embodiments, the layer comprising Skyrmions includes a material comprising one or more of: Fe, Co, Si, Mn, Ge, O, La, Zn, or Sr. In some embodiments, the first and second contacts comprise non-magnetic metals. In some embodiments, the voltage source is an Alternating Current (AC) voltage source.

[0080] In another example, a system is provided which comprises: a memory; a processor coupled to the memory, the processor including an apparatus according to the apparatus described above; and a wireless interface for allowing the processor to communicate with another device.

[0081] In another example, an apparatus is provided which comprises: means for forming a current source; means for coupling a first terminal of a bias tee to the current source; means for forming a skyrmion spin oscillator (SSO); means for coupling the SSO to a second terminal of the bias tee; and means for providing an oscillating signal from the SSO to a load coupled to a third terminal of the bias tee. In some embodiments, the SSO comprises a material which includes a material comprising one or more of: $Fe_{0.5}Co_{0.5}Si$, MnSi, FeGe,

$Co_9Zn_9Mn_2$, $Co_{10}Zn_{10}$, $La_3Mn_2O_7$, or $Sr_3Mn_2O_7$. In some embodiments, the SSO comprises of a material which includes a material comprising one or more of: Fe, Co, Si, Mn, Ge, O, La, Zn, or Sr.

[0082] In another example, a system is provided which comprises: a memory; a processor coupled to the memory, the processor including an apparatus according to the apparatus described above; and a wireless interface for allowing the processor to communicate with another device.

[0083] While the disclosure has been described in conjunction with specific embodiments thereof, many alternatives, modifications and variations of such embodiments will be apparent to those of ordinary skill in the art in light of the foregoing description. The embodiments of the disclosure are intended to embrace all such alternatives, modifications, and variations as to fall within the broad scope of the appended claims.

[0084] In addition, well known power/ground connections to integrated circuit (IC) chips and other components may or may not be shown within the presented figures, for simplicity of illustration and discussion, and so as not to obscure the disclosure. Further, arrangements may be shown in block diagram form in order to avoid obscuring the disclosure, and also in view of the fact that specifics with respect to implementation of such block diagram arrangements are highly dependent upon the platform within which the present disclosure is to be implemented (i.e., such specifics should be well within purview of one skilled in the art). Where specific details (e.g., circuits) are set forth in order to describe example embodiments of the disclosure, it should be apparent to one skilled in the art that the disclosure can be practiced without, or with variation of, these specific details. The description is thus to be regarded as illustrative instead of limiting.

[0085] An abstract is provided that will allow the reader to ascertain the nature and gist of the technical disclosure. The abstract is submitted with the understanding that it will not be used to limit the scope or meaning of the claims. The following claims are hereby incorporated into the detailed description, with each claim standing on its own as a separate embodiment.

CLAIMS

What is claimed is:

1. An apparatus comprising:
   a first contact;
   a second contact;
   a layer comprising Skyrmions coupled to the first and second contacts; and
   a voltage source coupled to the first and second contacts.

2. The apparatus of claim 1, wherein the layer comprising Skyrmions includes a material comprising one or more of: $Fe_{0.5}Co_{0.5}Si$, MnSi, FeGe, $Co_9Zn_9Mn_2$, $Co_{10}Zn_{10}$, $La_3Mn_2O_7$, or $Sr_3Mn_2O_7$.

3. The apparatus of claim 1, wherein the layer comprising Skyrmions includes a material comprising one or more of: Fe, Co, Si, Mn, Ge, O, La, Zn, or Sr.

4. The apparatus of claim 1, wherein the first and second contacts comprise non-magnetic metals.

5. The apparatus according to any one of claims 1 to 4, wherein the voltage source is an Alternating Current (AC) voltage source.

6. An apparatus comprising:
   a current source;
   a bias tee having a first terminal coupled to the current source;
   a skyrmion spin oscillator (SSO) coupled to a second terminal of the bias tee; and
   a load coupled to a third terminal of the bias tee.

7. The apparatus of claim 6, wherein the SSO comprises a material which includes one or more of: $Fe_{0.5}Co_{0.5}Si$, MnSi, FeGe, $Co_9Zn_9Mn_2$, $Co_{10}Zn_{10}$, $La_3Mn_2O_7$, or $Sr_3Mn_2O_7$.

8. The apparatus of claim 6, wherein the SSO includes a material comprising one or more of: Fe, Co, Si, Mn, Ge, O, La, Zn, or Sr.

9. A method comprising:
   forming a first contact;

forming a second contact;

forming a layer comprising Skyrmions coupled to the first and second contacts; and

coupling a voltage source to the first and second contacts.

10. The method of claim 9, wherein the layer comprising Skyrmions which includes a material comprising one or more of: $Fe_{0.5}Co_{0.5}Si$, MnSi, FeGe, $Co_9Zn_9Mn_2$, $Co_{10}Zn_{10}$, $La_3Mn_2O_7$, or $Sr_3Mn_2O_7$.

11. The method of claim 9, wherein the layer comprising Skyrmions which includes a material comprising one or more of: Fe, Co, Si, Mn, Ge, O, La, Zn, or Sr.

12. The method according to any one of claims 9 to 11, wherein the first and second contacts comprise non-magnetic metals.

13. The method according to any one of claims 9 to 11, wherein the voltage source is an Alternating Current (AC) voltage source.

14. A method comprising:

forming a current source;

coupling a first terminal of a bias tee to the current source;

forming a skyrmion spin oscillator (SSO);

coupling the SSO to a second terminal of the bias tee; and

providing an oscillating signal from the SSO to a load coupled to a third terminal of the bias tee.

15. The method of claim 14, wherein the SSO comprises a material which includes a material comprising one or more of: $Fe_{0.5}Co_{0.5}Si$, MnSi, FeGe, $Co_9Zn_9Mn_2$, $Co_{10}Zn_{10}$, $La_3Mn_2O_7$, or $Sr_3Mn_2O_7$.

16. The method of claim 14, wherein the SSO comprises of a material which includes a material comprising one or more of: Fe, Co, Si, Mn, Ge, O, La, Zn, or Sr.

17. An apparatus comprising means for performing a method according to any one of claims 9 to 13.

18. An apparatus comprising means for performing a method according to any one of claims 14 to 16.

19. A system comprising:

a memory;

a processor coupled to the memory, the processor including an apparatus according to any one of apparatus claims 1 to 5 or claims 6 to 8; and

a wireless interface for allowing the processor to communicate with another device.

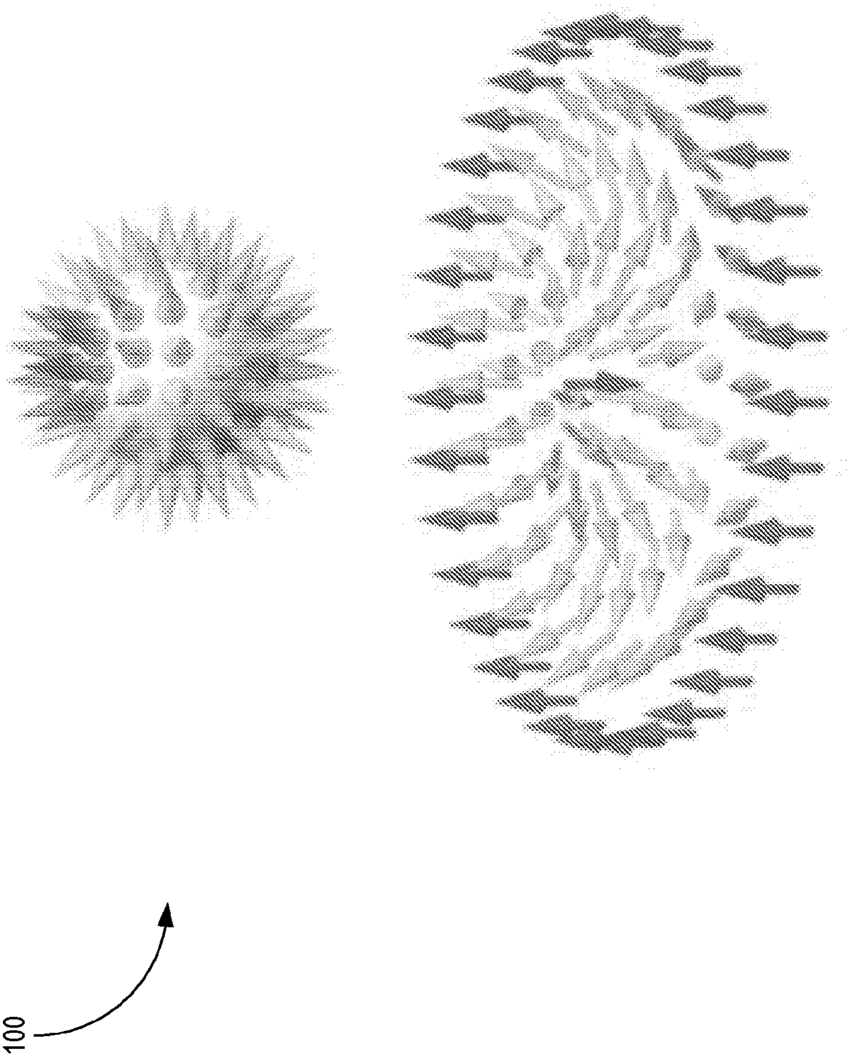

Fig. 1

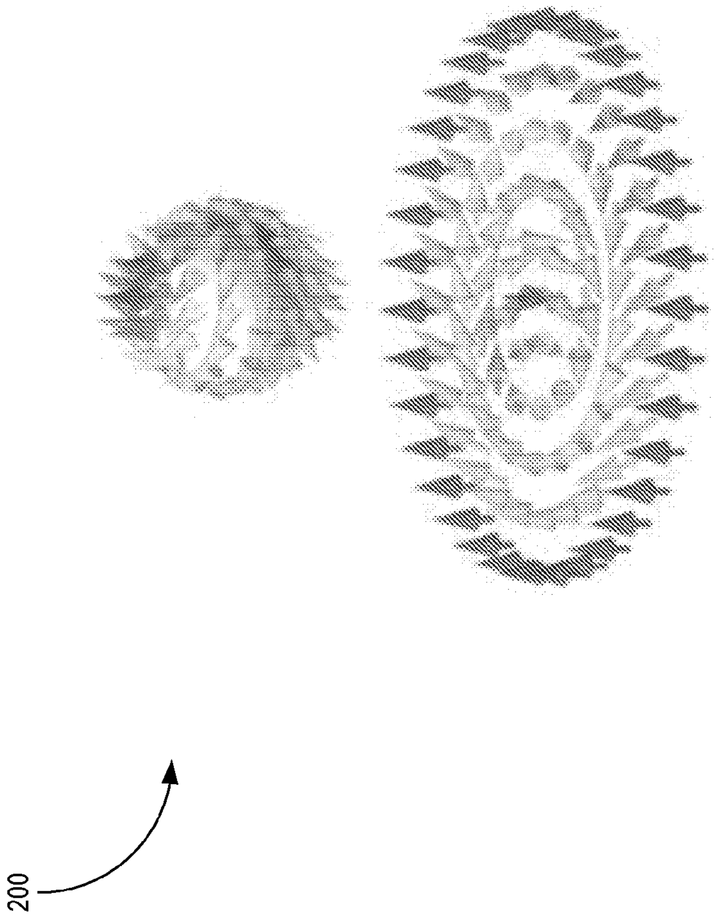

Fig. 2

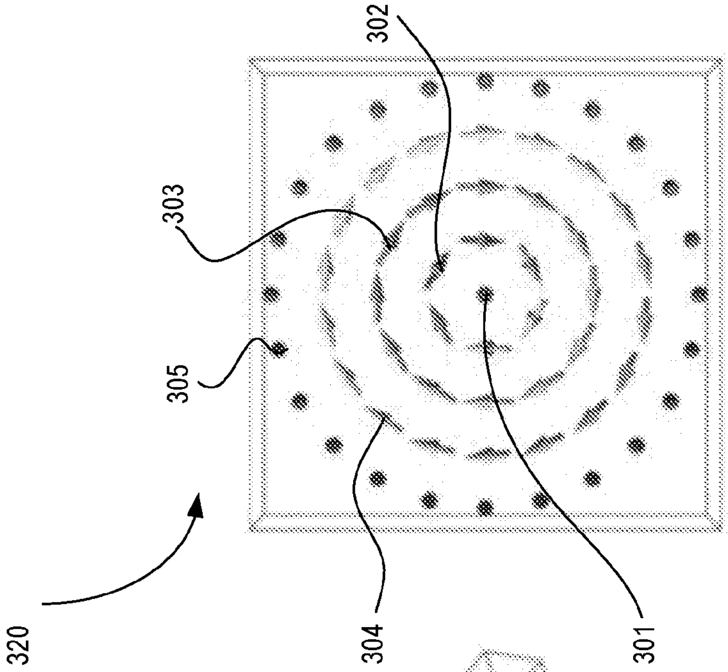

Fig. 3B

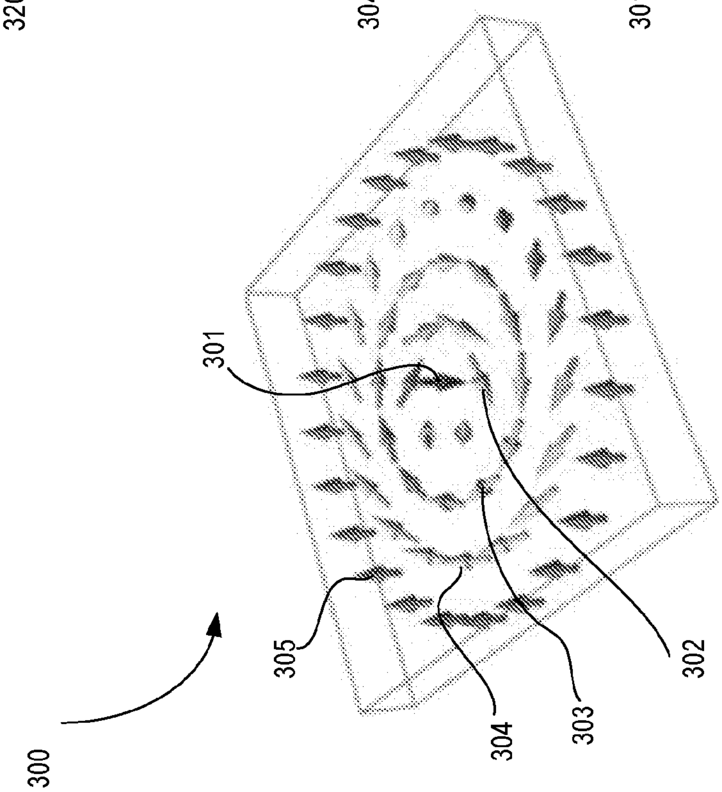

Fig. 3A

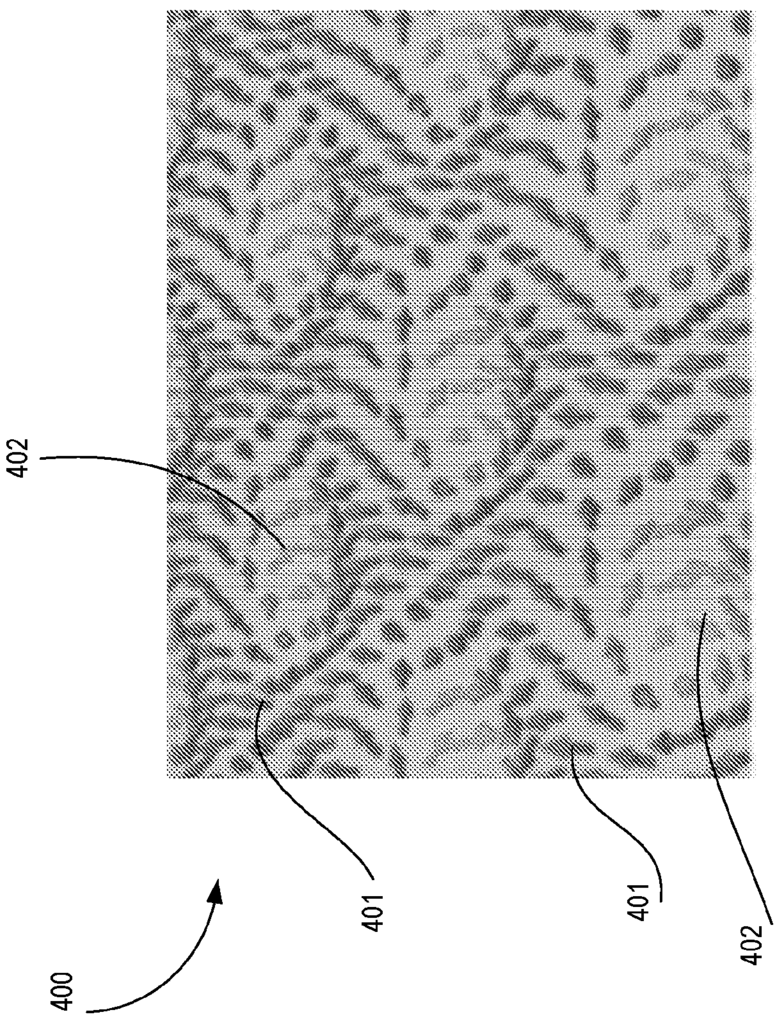

Fig. 4

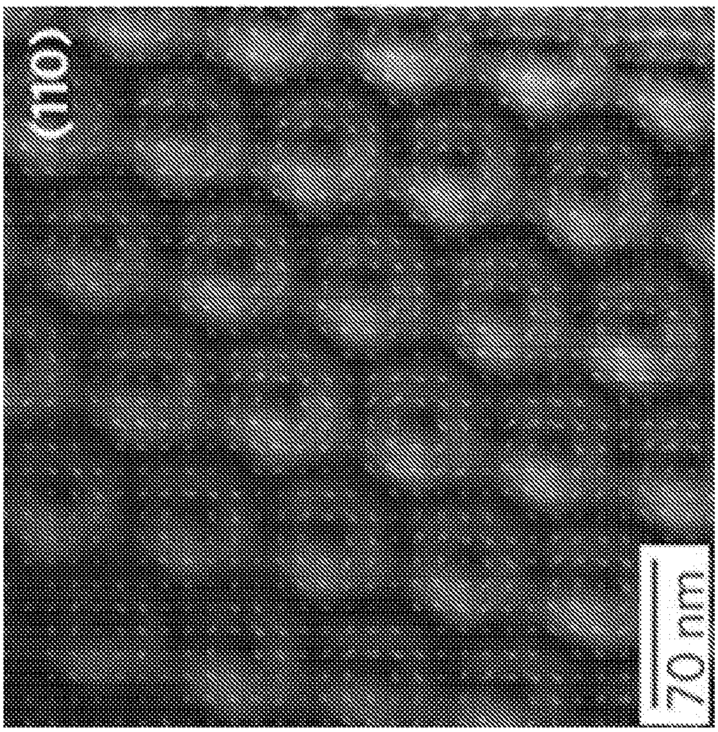

Fig. 5

500

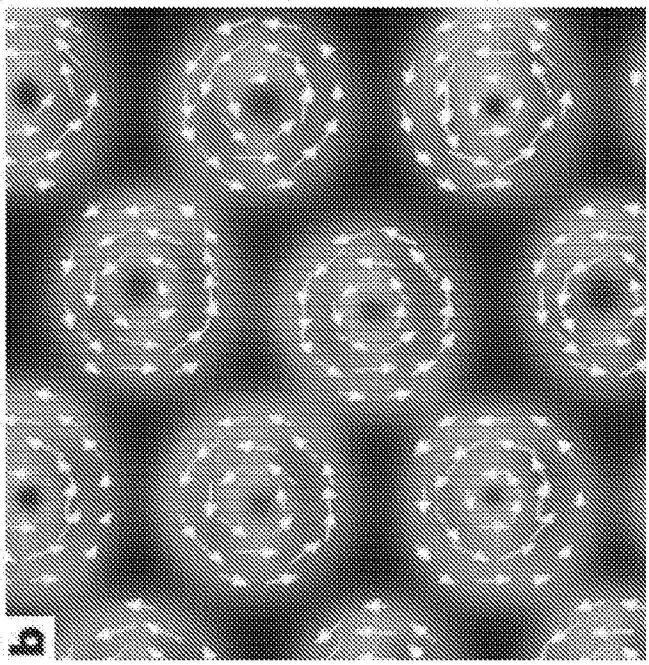

Fig. 6

600

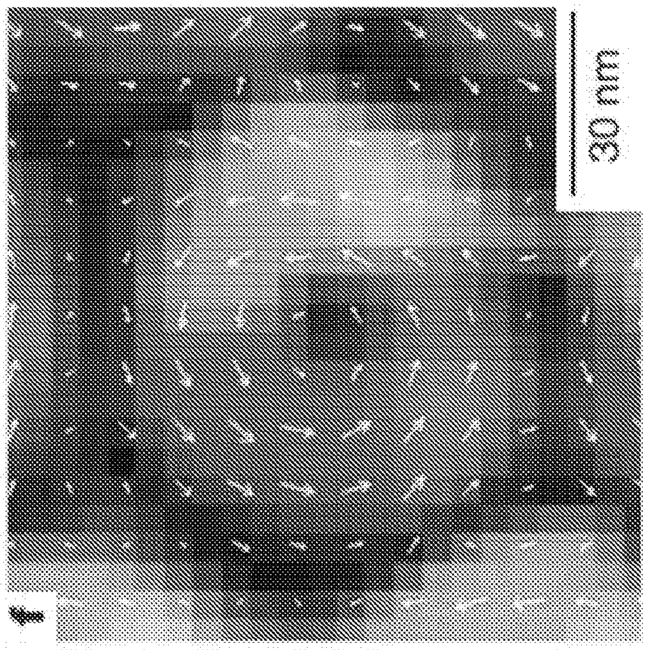

Fig. 7

700

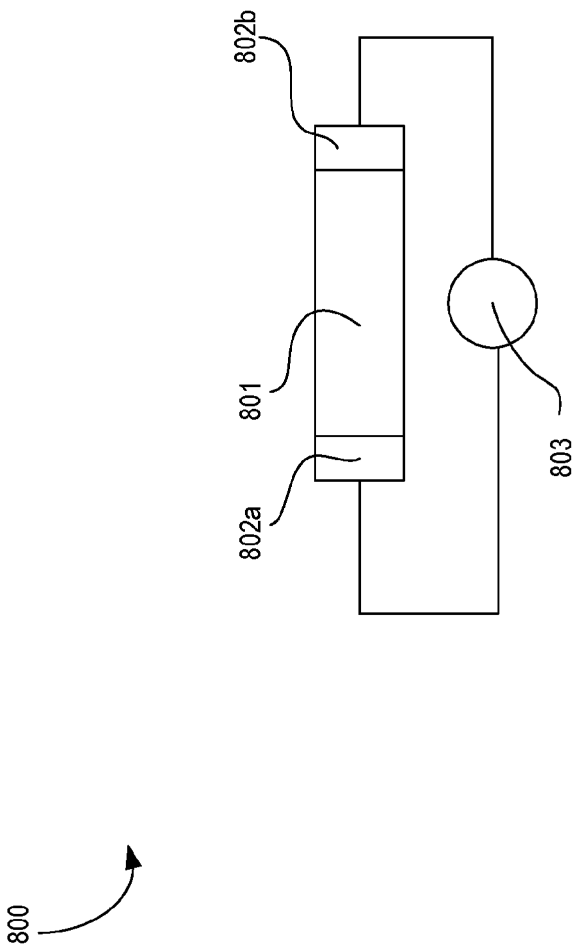

Fig. 8

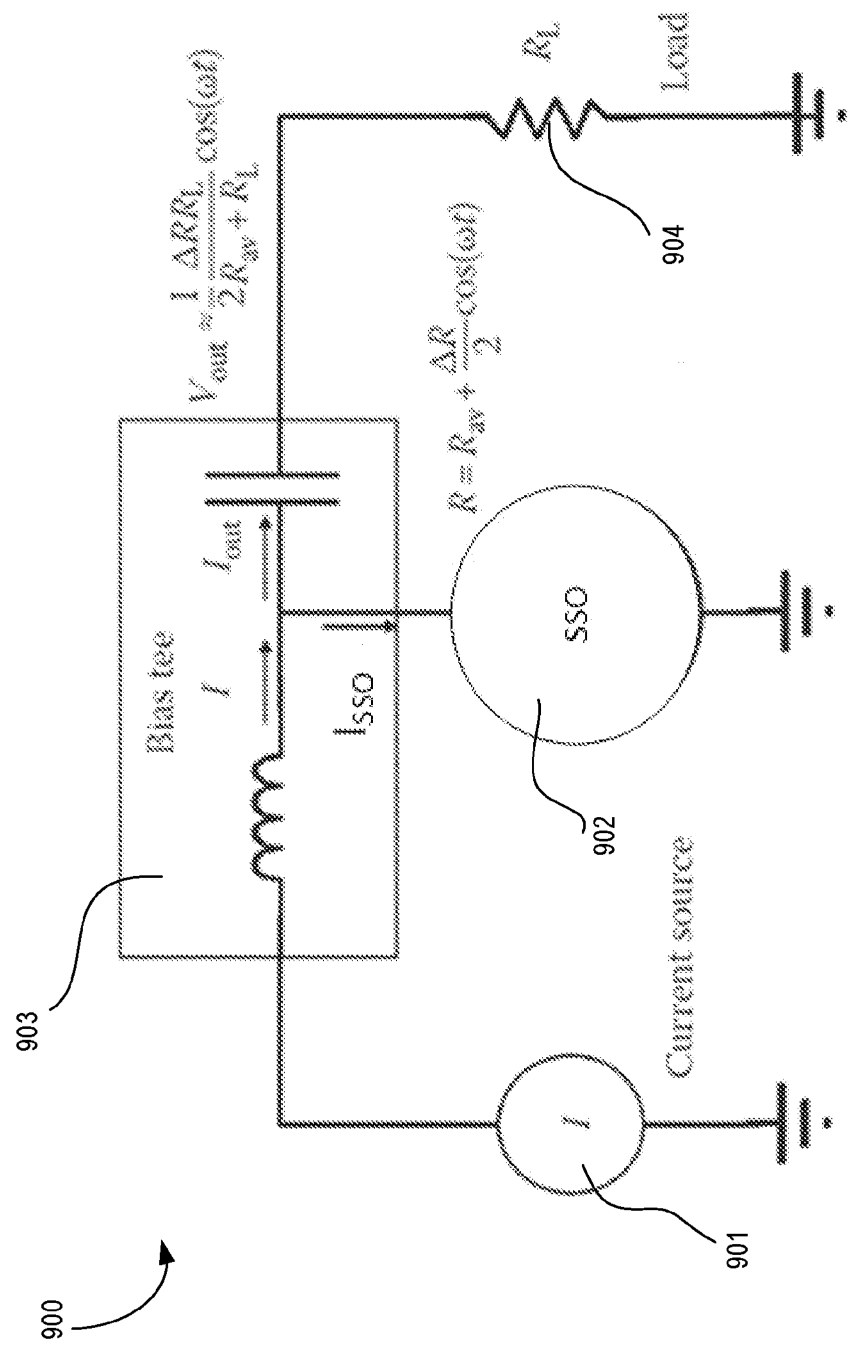
900
901
902
903
904
Bias tee
I
I_{out}
I_{SSO}
SSO
I
Current source
$R = R_{av} + \frac{\Delta R}{2}\cos(\omega t)$
$V_{out} = \frac{1}{2}\frac{\Delta R R_L}{R_{av} + R_L}\cos(\omega t)$
R_L
Load

Fig. 9

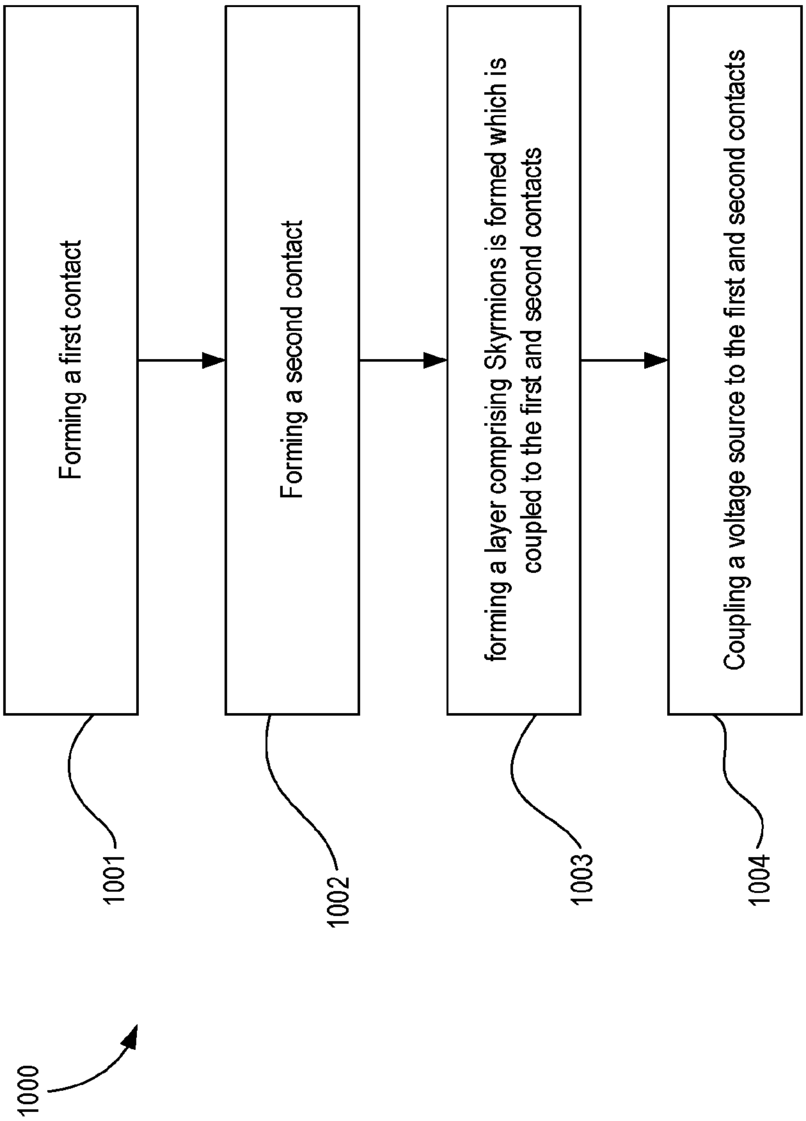
Forming a first contact
Forming a second contact
forming a layer comprising Skyrmions is formed which is coupled to the first and second contacts
Coupling a voltage source to the first and second contacts
1001
1002
1003
1004
1000

Fig. 10

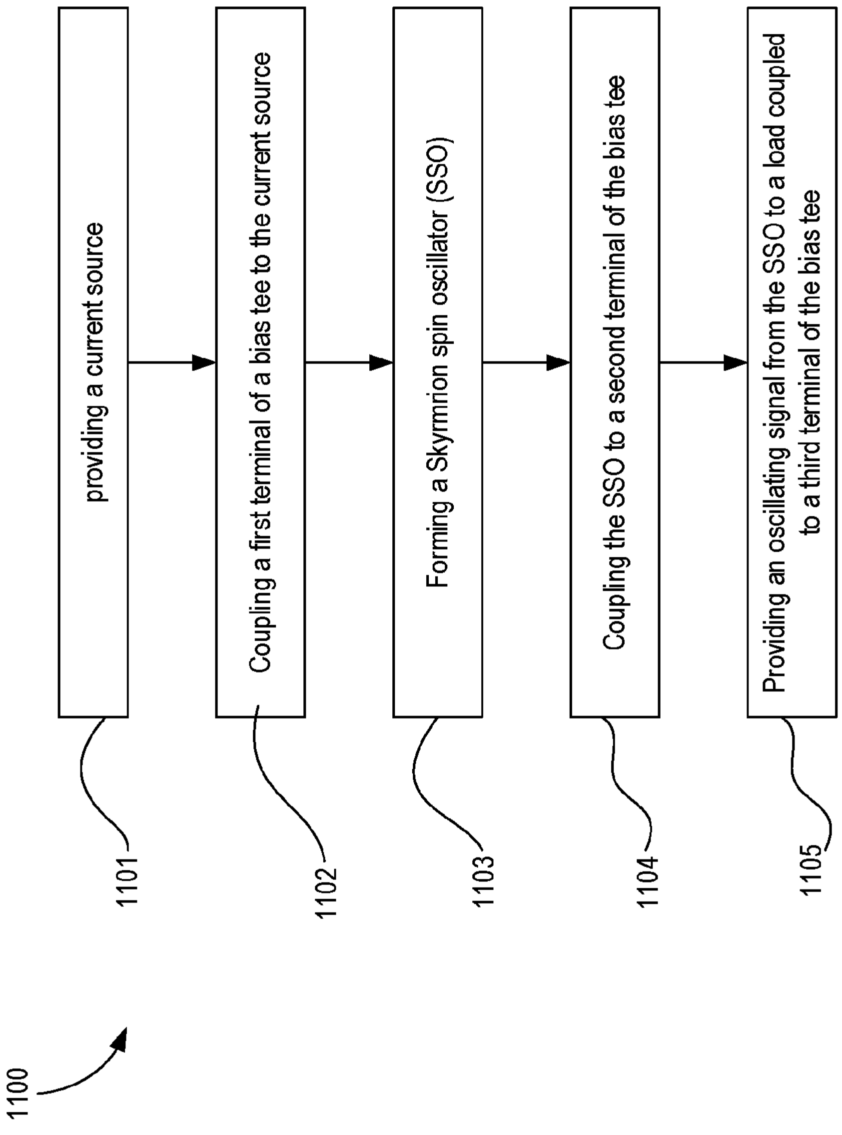
1100
providing a current source
1101
Coupling a first terminal of a bias tee to the current source
1102
Forming a Skyrmrion spin oscillator (SSO)
1103
Coupling the SSO to a second terminal of the bias tee
1104
Providing an oscillating signal from the SSO to a load coupled to a third terminal of the bias tee
1105

Fig. 11

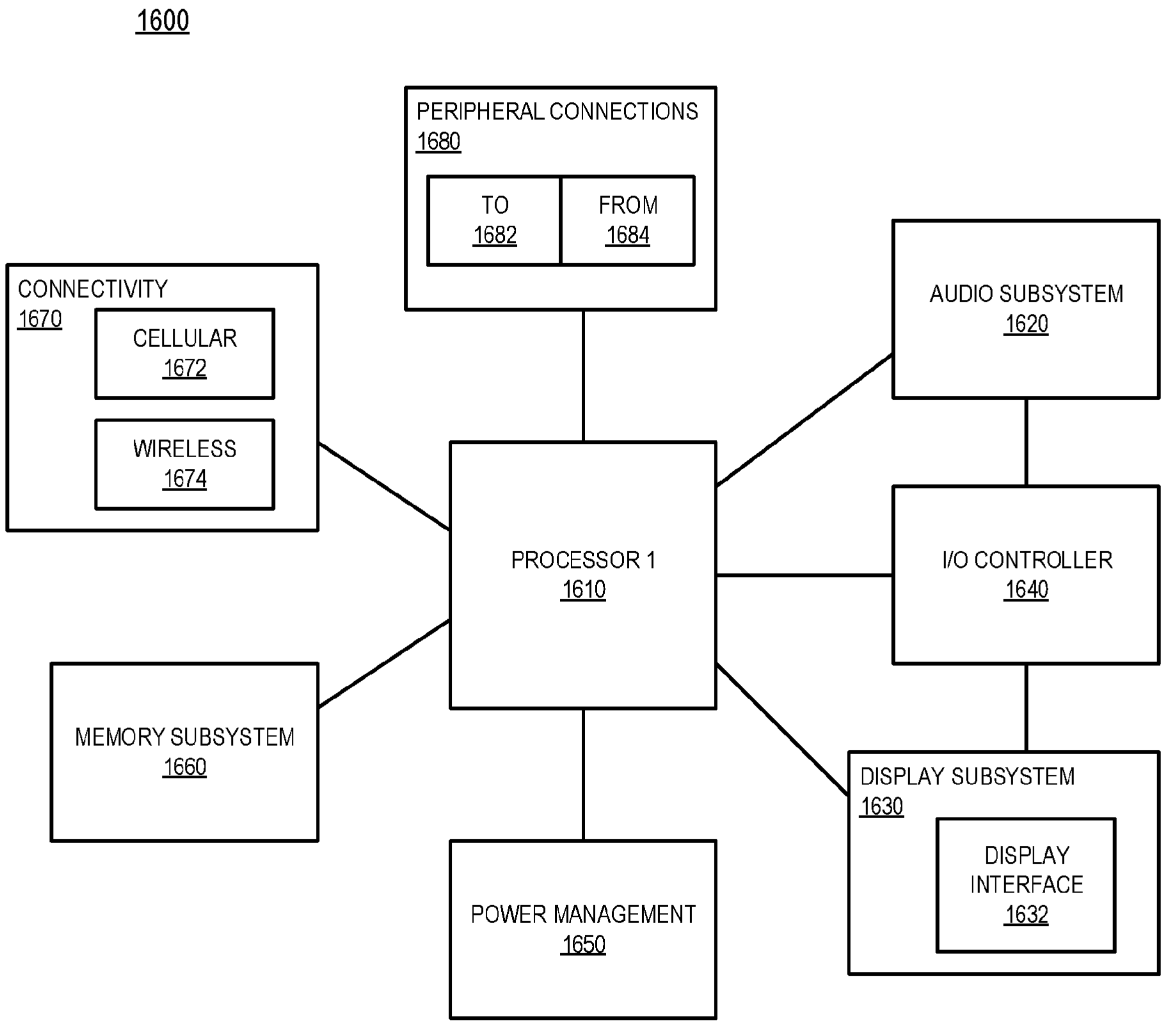
1600
PERIPHERAL CONNECTIONS
1680
TO
1682
FROM
1684
CONNECTIVITY
1670
CELLULAR
1672
WIRELESS
1674
AUDIO SUBSYSTEM
1620
PROCESSOR 1
1610
I/O CONTROLLER
1640
MEMORY SUBSYSTEM
1660
DISPLAY SUBSYSTEM
1630
DISPLAY
INTERFACE
1632
POWER MANAGEMENT
1650

Fig. 12

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/065393

A. CLASSIFICATION OF SUBJECT MATTER

H03B 15/00(2006.01)i, H01F 10/32(2006.01)i

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H03B 15/00; H01L 43/12; H03L 7/26; G11C 11/16; H01L 27/105; H01L 29/82; H01L 43/10; H01F 10/32

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: skyrmion, oscillator, voltage/current source, wireless, magnetic

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	SENFU ZHANG et al. `Current-induced magnetic skyrmions oscillator`. New Journal of Physics. 18 February 2015, Vol. 17, pages 1-13. See pages 1-2, 6-7 and figures 1, 6.	1-18 19
Y	US 2015-0200003 A1 (CORNELL UNIVERSITY) 16 July 2015 See paragraph [0037] and figures 1, 10.	19
A	US 2015-0085569 A1 (TAKAYUKI NOZAKI et al.) 26 March 2015 See paragraphs [0097]-[0118] and figures 1-3.	1-19
A	JP 2014-175417 A (INSTITUTE OF PHYSICAL & CHEMICAL RESEARCH) 22 September 2014 See paragraphs [0053]-[0056] and figure 5.	1-19
A	US 2014-0111283 A1 (INTEL CORPORATION) 24 April 2014 See paragraphs [0023]-[0029] and figures 3a-3b.	1-19

☐ 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	Date of mailing of the international search report
20 February 2017 (20.02.2017)	**20 February 2017 (20.02.2017)**

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2016/065393

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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		US 9460769 B2	04/10/2016
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JP 2014-175417 A	22/09/2014	None	
US 2014-0111283 A1	24/04/2014	TW 201234764 A	16/08/2012
		TW I551035 B	21/09/2016
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		US 2016-0079920 A1	17/03/2016
		US 8604886 B2	10/12/2013
		US 9252796 B2	02/02/2016
		WO 2012-087551 A1	28/06/2012