



(51) International Patent Classification:

H01F 10/32 (2006.01) *G11B 5/00* (2006.01)
H01L 29/66 (2006.01) *H01F 10/12* (2006.01)
C22C 19/07 (2006.01)

(21) International Application Number:

PCT/SG2015/050448

(22) International Filing Date:

12 November 2015 (12.11.2015)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

10201407461Q 12 November 2014 (12.11.2014) SG

(71) Applicant: AGENCY FOR SCIENCE, TECHNOLOGY
AND RESEARCH [SG/SG]; 1 Fusionopolis Way, #20-
10, Connexis, Singapore 138632 (SG).(72) Inventors: WONG, Hon Seng; c/o Data Storage Institute,
2 Fusionopolis Way, #08-01, Innovis, Singapore 138634
(SG). ZHOU, Tiejun; c/o Data Storage Institute, 2 Fu-
sionopolis Way, #08-01, Innovis, Singapore 138634 (SG).
CHUNG, Hong Jing; c/o Data Storage Institute, 2 Fu-
sionopolis Way, #08-01, Innovis, Singapore 138634 (SG).
ZHANG, Mingsheng; c/o Data Storage Institute, 2 Fu-
sionopolis Way, #08-01, Innovis, Singapore 138634 (SG).(74) Agent: ALLEN & GLEDHILL LLP; One Marina
Boulevard #28-00, Singapore 018989 (SG).(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, 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,
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).

Published:

— with international search report (Art. 21(3))

(54) Title: SPIN TORQUE OSCILLATOR WITH COIR-RH OSCILLATION LAYER

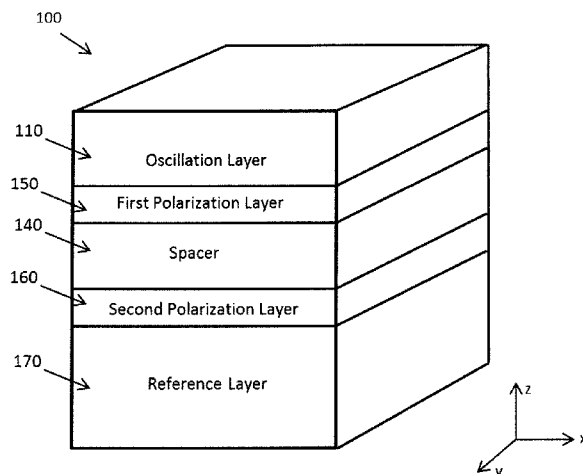


FIG. 1

(57) Abstract: A spin torque oscillator (STO) comprises an oscillation layer configured to generate a high frequency magnetic field with a low driving current wherein the oscillation layer is made of an alloy $\text{Co}_{85}\text{Ir}_{(15-x)}\text{Rh}_x$ where x is about 1 to 14 at %, thereby improving performance of the STO in terms of the driving current, oscillation frequency, magnetic field, coercivity, etc. The STO also comprises a reference layer to induce a magnetization precession in the oscillation layer and at least one polarization layer disposed between the oscillation layer and the reference layer to enhance the spin polarization rate of the STO. The oscillation layer may comprise a first oscillation layer and a second oscillation layer in which an interlayer is disposed between them. The interlayer is configured with a suitable material so as the first and second oscillation layers are coupled ferromagnetically or anti-ferromagnetically.

Spin Torque Oscillator with Colr-Rh Oscillation Layer**Field of the Invention**

The present invention relates to a spin torque oscillator, particularly, a spin torque oscillator having an oscillation layer made of alloy Colr-Rh. More particularly, the oscillation layer of Colr-Rh is coupled with a polarization layer to further improve the efficiency of the spin torque oscillator.

Background of the Invention

The exponential increase in data volumes demands new technologies to maintain a high growth rate of magnetic recording density. Microwave-assisted magnetic recording (MAMR), a resonance-based technology, has been proposed to address the issue due to its lower energy consumption, easier integration with the current recording systems, etc, which capable of achieving a recording density of up to 3-4 Tb/in². One important part of MAMR technology is the spin torque oscillator (STO) for generating localized ac magnetic field in the microwave frequency regime of 25-40 GHz for effective writing operation.

For MAMR technology, writing information in a recording medium by a recording main pole of the magnetic head is assisted by a STO positioned adjacent to the recording main pole. The magnetic field generated by the recording main pole for writing information is typically not strong enough to switch the magnetization of a target recording area of the recording medium. Therefore, STO is configured to generate a high frequency magnetic field from the precession of magnetization in the oscillation layer of the STO which is intended to reduce the coercivity of the target recording area, thereby assisting the recording magnetic field to write information in the target recording area. Typically, a relatively high driving current is required to be applied to the STO in order to maintain a stable precession of magnetization in the oscillation layer for the generation of a high frequency magnetic field. This however may affect the reliability and efficiency of the STO due to excessive heat is generated. Therefore, a STO with a low driving current for a stable magnetization precession is desired.

A STO having an oscillation layer (also known as free layer or field generation layer) made of a negative magnetic anisotropic material has been proposed to improve the efficiency of STO. Among the choices of the suitable materials, alloy CoIr is a promising candidate due to its relatively high negative anisotropy energy density and easy of processing. However, doping of Ir (Iridium) into Co (Cobalt) to form alloy CoIr has the drawbacks of introducing a higher damping constant and a lower saturation magnetization which are detrimental to the performance of the STO. Consequently, a higher driving current is required for the STO to maintain the stability of magnetization precession in the oscillation layer, and at the same time lower oscillation frequency and magnetic field are achievable. Further, the use of CoIr as the oscillation layer of a STO may result in a poorer spin polarization that would also affect the performance of STO.

As such, there exists a need for an efficient STO which configured with suitable designs and materials that seek to overcome the aforementioned drawbacks.

Summary of the Invention

The above and other problems are solved and an advance in the art is made by a spin torque oscillator (STO) in accordance with the present invention. In the present invention, alloy $\text{Co}_{85}\text{Ir}_{(15-x)}\text{-Rh}_x$ (where x is about 1 to 14 at %) is used to form the oscillation layer of STO. Alloy CoIr-Rh is a high negative magnetic anisotropic material having a low damping constant and a high saturation magnetization. Further, at least one polarization layer is disposed between the oscillation layer and a reference layer of the STO to enhance the spin polarization rate of the STO. A STO configured in accordance with the present invention is more efficient than the conventional STO in terms of its lower driving current, higher oscillation or precession frequency, higher magnetic field, lower coercivity, etc. Further, a wide percentage of Rh (Rhodium), i.e. from about 1 to 14 at %, may be used to form the alloy CoIr-Rh with desirable properties, dependent on the application requirements. Apart from using in STO designs, alloy CoIr-Rh is also applicable in other applications, such as tunnel/giant magnetoresistance designs, patterned geometries (e.g. nanopillar and nanocontact), etc, where a magnetic oscillation system is utilised.

A spin torque oscillator in accordance with an embodiment of the present invention comprises an oscillation layer configured to generate a high frequency magnetic field with a

low driving current wherein the oscillation layer is made of an alloy $\text{Co}_{85}\text{Ir}_{(15-x)}\text{-Rh}_x$ where x is about 1 to 14 at %. A reference layer made of a magnetic material to induce a precession of magnetization in the oscillation layer. At least one polarization layer is disposed between the oscillation layer and the reference layer to enhance spin polarization rate of the spin torque oscillator. The high frequency magnetic field generated by the oscillation layer is about 500 to 1500 Oe, and the driving current is about 1 to 5 mA.

In some embodiments, the at least one polarization layer comprises a first polarization layer and a second polarization layer wherein the first polarization layer is coupled to the oscillation layer to enhance spin polarization rate of the oscillation layer and the second polarization layer is coupled to the reference layer to enhance spin polarization rate of the reference layer. The spin torque oscillator further comprises a spacer disposed between the first and second polarization layers wherein the spacer is made of a non-magnetic material.

In some embodiments, the oscillation layer comprises a first oscillation layer and a second oscillation layer. The first oscillation layer has a thickness of about 5 to 10 nm, and the second oscillation layer has a thickness of about 5 to 10 nm. The oscillation layer has a thickness of about 10 to 20 nm. In some embodiments, the oscillation layer having an anisotropy energy density (k_u) of about $-(0.5 \text{ to } 10) \times 10^6 \text{ erg/cm}^3$, a damping constant (α) of about 0.01 to 0.15, and a saturation magnetization (M_s) of about 800 to 1200 emu/cm³.

In some embodiments, the spin torque oscillator further comprises an interlayer disposed between the first and second oscillation layers so that the first and second oscillation layers are coupled ferromagnetically or anti-ferromagnetically. In an embodiment, the interlayer is made of Ru having a thickness of about 1.6 to 2.4 nm so that the first and second oscillation layers are coupled ferromagnetically. In another embodiment, the interlayer is made of Ru having a thickness of about 0.6 to 1.2 nm so that the first and second oscillation layers are coupled anti-ferromagnetically.

In some embodiments, the at least one polarization layer having a spin polarization rate of about 0.3 to 0.55, and a damping constant of about 0.01 to 0.02. In an embodiment, the at least one polarization layer is made of Co (Cobalt) having a thickness of about 0.5 to 1.0 nm. In another embodiment, the at least one polarization layer is made of a trilayer of

Co/Cu/Co (Cobalt/Copper/Cobalt) having a thickness of about 0.5 to 0.8 nm/0.2 to 0.5 nm/0.5 to 0.8 nm.

In some embodiments, the reference layer has an anisotropy energy density (k_u) of about $(0 \text{ to } 1) \times 10^7 \text{ erg/cm}^3$, and a saturation magnetization (M_s) of about 500 to 1000 emu/cm³. The reference layer has a magnetic anisotropy axis in a direction in-plane or perpendicular to the oscillation layer. The reference layer has a thickness of about 10 to 20 nm.

A method of fabricating a spin torque oscillator in accordance with an embodiment of the present invention comprises forming an oscillation layer for generating a high frequency magnetic field with a low driving current wherein the oscillation layer is made of an alloy $\text{Co}_{85}\text{Ir}_{(15-x)}\text{-Rh}_x$ where x is about 1 to 14 at %; forming a reference layer made of a magnetic material to induce a precession of magnetization in the oscillation layer; and forming at least one polarization layer between the oscillation layer and the reference layer to enhance spin polarization rate of the spin torque oscillator.

In some embodiments, the step of forming the at least one polarization layer comprises forming a first polarization layer and a second polarization layer wherein the first polarization layer is coupled to the oscillation layer to enhance spin polarization rate of the oscillation layer and the second polarization layer is coupled to the reference layer to enhance spin polarization rate of the reference layer. The method further comprises forming a spacer between the first and second polarization layers wherein the spacer is made of a non-magnetic material.

In some embodiments, the step of forming the oscillation layer comprises forming a first oscillation layer and a second oscillation layer. The method further comprises forming an interlayer between the first and second oscillation layers so that the first and second oscillation layers are coupled ferromagnetically or anti-ferromagnetically.

Brief Description of the Drawings

The above and other features and advantages of a spin torque oscillator (STO) in accordance with the present invention are described in the following description of preferred

embodiments with reference to the following figures:

FIG. 1 illustrates a schematic diagram of a STO in accordance with an embodiment of the present invention;

FIG. 2 illustrates a schematic diagram of a STO in accordance with a further embodiment of the present invention;

FIG. 3 illustrates the graphs of anisotropy energy density (K_u) and saturation magnetization (M_s) against different percentage of Rh from 0 to 15 at %;

FIG. 4 illustrates the graphs of coercivity (H_c) and XRD rocking curve against different percentage of Rh from 0 to 15 at %;

FIG. 5A illustrates a graph of damping constant (α) against different percentage of Rh from 0 to 15 at %;

FIG. 5B illustrates a graph of line width of ferromagnetic resonance (FMR), ΔH , against FMR frequency, with different percentage of Rh from 0 to 15 at %;

FIG. 6 illustrates the graphs of oscillation frequency and ac magnetic field (normalized) against different percentage of Rh from 0 to 15 at %, without external magnetic field;

FIG. 7A illustrates a graph of oscillation or precession frequency against different percentage of Rh from 0 to 15 at %, in the presence of external magnetic field at 0, 2000, 4000, 6000 and 8000 Oe;

FIG. 7B illustrates a graph of ac magnetic field (normalized) against different percentage of Rh from 0 to 15 at %, in the presence of external magnetic field at 0, 2000, 4000, 6000 and 8000 Oe;

FIG. 8 illustrates a graph of magnetic moment against applied magnetic field, for CoIr (0% Rh) and CoIr-Rh (2% Rh);

FIG. 9A illustrates a coercivity plot (H_c) at all angles (0 to 360 degree) with different percentage of Rh from 0 to 15 at %;

FIG. 9B and 9C are two coercivity plots with an enlarge scale for the same coercivity plot as illustrated in FIG. 9A; and

FIG. 10 illustrates a graph of magnetoresistance (MR) ratio against applied magnetic field with the polarization layer made of different materials coupled to the oscillation layer.

Detailed Description of the Invention

The present invention relates to a spin torque oscillator (STO) having an oscillation layer made of alloy $\text{Co}_{85}\text{Ir}_{(15-x)}\text{-Rh}_x$ where x represents the percentage of Rh which can be a value between 1 to 14 at %. Alloy CoIr-Rh is a high negative magnetic anisotropic material having a low damping constant and a high saturation magnetization, especially compared to alloy CoIr (without Rh). As such, the performance of STO may be improved in terms the driving current, oscillation or precession frequency, magnetic field, coercivity, etc, which will be discussed in the below. In this invention, a much lower driving current of the STO is required. For example, the driving current for a STO using $\text{Co}_{85}\text{Ir}_7\text{-Rh}_8$ (i.e. 8% Rh) as the oscillation layer is about 22% of the driving current required for a STO using CoIr as the oscillation layer. At least one polarization layer made of a suitable magnetic material (such as Co or Co/Cu/Co) is disposed between the oscillation layer and the reference layer of the STO for enhancing the spin polarization rate of the oscillation layer and/or the reference layer, thereby further improving the performance of the STO.

As mentioned, there are limitations of using alloy CoIr (without Rh) as the oscillation layer for a STO. It has been observed from experiments that alloy CoIr achieves an optimum negative anisotropy energy density (K_u) at about $-4.6 \times 10^6 \text{ erg/cm}^3$ when Co is 85% and Ir is 15% (i.e. $\text{Co}_{85}\text{Ir}_{15}$). In principle, with a proper negative magnetic anisotropic material chosen for the oscillation layer, the driving current of the STO may be greatly reduced due to lack of energy barrier in the magnetization precession plane. However for $\text{Co}_{85}\text{Ir}_{15}$ where the negative K_u is at the optimum as stated above, its damping constant (α) is at a very high value of about 0.216. Further, it has also been observed that the saturation magnetization (M_s) of CoIr is decreasing from about 1200 to 800 emu/cm³ when Ir is increasing from 0% to 15%. An

oscillation layer with a higher damping constant and a lower saturation magnetization has a direct implication of a higher driving current required for the STO, and at the same time lower oscillation or precession frequency and magnetic field are achievable by the STO. Hence, based on the observations, using Colr as the oscillation layer is generally unfavourable.

To address the above issues, the present application introduces the use of alloy $\text{Co}_{85}\text{Ir}_{(15-x)}\text{-Rh}_x$ (x is about 1 to 14 at %) as the oscillation layer of STO. Although replacing Ir with Rh may result in a reduction of orbital moment (due to smaller atomic radii), the spin moment increases and thus K_u may be improved slightly or at least maintains at a high value, thereby reducing the damping constant. Alloy Colr-Rh is a relatively high negative magnetic anisotropic material (high negative K_u) having a lower damping constant (α) and a higher saturation magnetization (M_s) than alloy Colr. Further, at least one polarization layer is disposed between the oscillation layer and the reference layer to enhance the spin polarization rate of the STO. Such configuration is advantageously reducing the driving current of the STO, as well as increasing the oscillation or precession frequency and the magnetic field generated the STO. Further, a wide range of percentage of Rh (from about 1 to 14 at %) may be used to form alloy Colr-Rh, with desirable properties. The present invention is applicable in any STO designs which utilise Colr-Rh as its oscillation layer regardless of whether the reference layer of the STO has a magnetic anisotropy axis in a direction in-plane or perpendicular to the oscillation layer.

FIG. 1 illustrates a schematic diagram of a basic structure of STO 100 in accordance to an embodiment of the present invention. STO 100 comprises oscillation layer 110 (also known as free layer or field generation layer), spacer 140, first polarization layer 150, second polarization layer 160 and reference layer 170. A typical dimension of STO 100 may be about 40 x 40 x 30 nm (in x-y-z direction as shown in FIG. 1). In operation, a driving current is applied to STO 100 so that a high frequency ac magnetic field may be generated. In this regard, electron spins passing through reference layer 170 are polarized based on the direction of magnetization in reference layer 170 which produces a spin polarized current. This spin polarized current is transmitted through spacer 140 and applies a spin transfer torque on oscillation layer 110 which causes the magnetization of oscillation layer 110 to oscillate into a precession state, thereby generating a high frequency ac magnetic field. STO 100 may also have other layers which are not explicitly discussed here, such as substrate layer, adhesive layer, seedlayer, intermediate layer, cap layers, etc.

Oscillation layer 110 is made of alloy $\text{Co}_{85}\text{Ir}_{(15-x)}\text{-Rh}_x$ where x represents the percentage of Rh which may be a value between about 1 and 14 at %. For an example, oscillation layer 110 may be made of alloy $\text{Co}_{85}\text{Ir}_7\text{-Rh}_8$ where Co = 85%, Ir = 7% and Rh = 8%. Preferably, x is no more than 12 at %. Alloy $\text{Co}_{85}\text{Ir}_{(15-x)}\text{-Rh}_x$ may have a high negative anisotropy energy density (K_u) of about $-(0.5 \text{ to } 10) \times 10^6 \text{ erg/cm}^3$, more particularly about $-(3.0 \text{ to } 5.0) \times 10^6 \text{ erg/cm}^3$; a low damping constant (α) of about 0.01 to 0.15, more particularly about 0.045 to 0.075; and a high saturation magnetization (M_s) of about 800 to 1200 emu/cm^3 , more particularly about 850 to 1000 emu/cm^3 . The driving current of STO 100 with oscillation layer 110 made of $\text{Co}_{85}\text{Ir}_{(15-x)}\text{-Rh}_x$ may be as low as 1 mA, or about 1 to 5 mA in some embodiments. Alloy $\text{Co}_{85}\text{Ir}_{(15-x)}\text{-Rh}_x$ can be formed by a deposition process, such as UHV sputtering at room temperature, where Ir and Rh are incorporated into Co. Oscillation layer 110 may have a thickness of about 10 to 20 nm, more particularly about 10 nm.

At least one polarization layer is disposed between oscillation layer 110 and reference layer 170 for enhancing spin polarization rate of STO. In an embodiment as shown in FIG. 1, there are two polarization layers, i.e. first polarization layer 150 disposed between oscillation layer 110 and spacer 240 for improving the spin polarization rate of oscillation layer 110, and second polarization layer 160 disposed between reference layer 170 and spacer 140 for improving the spin polarization rate of reference layer 170. Polarization layers 150 & 160 are made of a suitable magnetic material which has a high spin polarization rate (η), such as about 0.3 to 0.55 and more particularly about 0.4 to 0.5, and a low damping constant (α), such as about 0.01 to 0.02. In an embodiment, first polarization layer 150 and/or second polarization layer 160 may be made of Co having a thickness of about 0.5 to 1.0 nm. In another embodiment, first polarization layer 150 and/or second polarization layer 160 may be made of a trilayer of Co/Cu/Co having a thickness of about 1.2 to 1.9 nm corresponding to 0.5 to 0.8 nm (Co)/ 0.2 to 0.5 nm (Cu)/ 0.5 to 0.8 nm (Co).

In some embodiments, a STO may comprise one polarization layer only, such as only first polarization layer 150 disposed below oscillation layer 110. It is possible that the spin polarization rate of oscillation layer 110 be improved by about 20% with the presence of polarization layer 150. Polarization layer 150 coupled with oscillation layer 110 made of CoIr-Rh may further reduce the driving current that is needed to establish a stable magnetization precession in oscillation layer 110. Due to low damping constant and high polarization rate of

polarization layer 150, the driving current of STO 100 may be reduced by about 10% to 20%. This is because polarization layer 150 (which has high η and low α) may increase the spin polarization rate and reduce the damping constant of oscillation layer 110, thereby further improving the efficiency of STO 100.

STO 100 further comprises spacer 140 disposed between first and second polarization layers 150 & 160. Spacer 140 is made of a non-magnetic material, such as Cu, Cr, Ag, or Au, and may have a thickness of about 2 to 5 nm. Reference layer 170 is disposed below second polarization layer 160 for inducing a precession of magnetization in oscillation layer 110. Reference layer 170 is made of a suitable magnetic material, such as Co/Pt, Co/Pd, CoPt or FePt which having perpendicular magnetic anisotropy energy; such as Co, Fe or CoFe which having in-plane magnetic anisotropy energy. The spin polarization rate of reference layer 170 may be enhanced by second polarization layer 160. Preferably, reference layer 170 is made of a magnetic material having K_u of about $(0 \text{ to } 1) \times 10^7 \text{ erg/cm}^3$ and M_s of about 500 to 1000 emu/cm³. Reference layer 170 may have a magnetic anisotropy axis in a direction in-plane or perpendicular to oscillation layer 110. Reference layer 170 may have a thickness of about 10-20 nm.

FIG. 2 illustrates a schematic diagram of STO 200 according to a further embodiment of the present invention. Polarization layers 250 & 260, reference layer 270, and spacer 240 may be configured to be the same as polarization layers 150 & 160, reference layer 170, and spacer 140 of STO 100 as discussed above. However, in this embodiment, STO 200 comprises two oscillation layers, i.e. first oscillation layer 210 and second oscillation layer 220, and an interlayer 230 disposed between first and second oscillation layers 210 & 220. Oscillation layers 210 & 220, polarization layers 250 & 260, reference layer 270, and spacer 240 may be made of the same materials as oscillation layer 110, polarization layers 150 & 160, reference layer 170, and spacer 140 of STO 100 respectively. Interlayer 230 is configured and made of a suitable material, e.g. Ru (Ruthenium), such that first oscillation layer 210 and second oscillation layer 220 can be coupled ferromagnetically or anti-ferromagnetically. In one embodiment, interlayer 230 is made of Ru with a thickness of about 1.6 to 2.4 nm so as a ferromagnetic coupling is formed between first and second oscillation layers 210 & 220. In another embodiment, interlayer 230 is made of Ru with a thickness of 0.6 to 1.2 nm so as an anti-ferromagnetic coupling is formed between first and second oscillation layers 210 & 220. First oscillation layer 210, as well as second oscillation layer 220, may have a thickness of

about 5 to 10 nm. A typical dimension of STO 200 may be about 40 x 40 x 30 nm (in x-y-z direction as shown in FIG. 2).

In the following, various properties of alloy $\text{Co}_{85}\text{Ir}_{(15-x)}\text{-Rh}_x$ as the oscillation layer are discussed. FIG. 3 illustrates the graphs of anisotropy energy density (K_u) and saturation magnetization (M_s) against different percentage of Rh from 0 to 15 at %. The K_u graph shows that replacement of some Ir by Rh may result in a slight improvement in K_u (i.e. more negative; from about -4.5×10^6 to -4.9×10^6 erg/cm³) at less than 5% Rh, followed by a decrease in K_u (i.e. less negative) beyond 5% Rh which is due to the decrease in orbital moment when more Ir atoms are replaced by Rh atoms (smaller atomic radii). Further, the M_s graph shows that M_s increases from about 820 to 1020 emu/cm³ when Rh is varied from 0 to 15 at % which is due to the increase in spin moment when more Rh atoms are incorporated to form CoIr-Rh. It is understood that an increase in M_s is necessary for a STO to generate a higher magnetic field. In conclusion, it is clear from the graphs that alloy CoIr-Rh with an appropriate percentage of Rh can have a better K_u and M_s than alloy CoIr (i.e. Rh = 0 at %).

FIG. 4 illustrates the graphs of coercivity (H_c) and XRD rocking curve against different percentage of Rh from 0 to 15 at %. A drastic drop in the coercivity by at least half is observed at about 5% Rh (drop from about 260 to 105 Oe), and continues to decrease beyond 5% Rh. The decrease in coercivity means that CoIr-Rh becomes magnetically softer which advantageously for use as an oscillator layer as compared to conventional STO that utilises soft in-plane magnetic materials. Further, the rocking curve shows a reduction from about 8.7 to 6.4 degree when Rh is varied from 0 to 15 at % which is associated to the improvement of crystallinity of CoIr-Rh.

FIG. 5A illustrates a graph of damping constant (α) against different percentage of Rh from 0 to 15 at %. A reduction of α by nearly half is observed at about 5% Rh (drop from about 0.22 to 0.1). The reduction in α is important for performance improvement in STO in order to achieve a lower driving current (such as about 50% reduction in driving current) for magnetization precession and a higher oscillation frequency given the same current. The relationship between the driving current, damping constant and oscillation frequency (and other parameters) may be reflected in the following equations:

$$I_s = - \frac{2\alpha e \mu_0 V M_s \left[H_{az} + \frac{2K_u}{\mu_0 M_s} \cos \theta + M_s (N_x - N_z) \cos \theta \right]}{\hbar G(\theta)}$$

$$G(\theta) = \left[-4 + (1 - P)^3 \cdot \frac{3 + \cos \theta}{4P^{3/2}} \right]^{-1}$$

$$\omega = -\frac{I_s \gamma_0 \hbar G(\theta)}{2\alpha e \mu_0 V M_s}$$

where I_s is the driving current, e is the charge of an electron (-1.6×10^{-19} C), μ_0 is the permeability of free space, V is the volume of the oscillation layer, H_{az} is the total applied magnetic field on the oscillation layer, N_x and N_z are the demagnetizing factors of the oscillation layer, $\hbar$ is the Planck constant, $G(\theta)$ is the spin transfer efficiency function, ω is the oscillation frequency, γ_0 is the gyromagnetic factor, and P is the polarization of conduction electrons. From the equations, it is clear that the decrease in α will thus reduce the driving current or increase the oscillation frequency, thereby improving the performance of STO. FIG. 5B illustrates a graph of line width of ferromagnetic resonance (FMR), ΔH , against FMR frequency, with different percentage of Rh from 0 to 15 at %. It is shown that FWHM (full width at half maximum) of FMR spectrum reduces with increasing of Rh doping. The damping constant of FIG. 5A is derived from FIG. 5B.

FIG. 6 illustrates the graphs of oscillation or precession frequency and ac magnetic field (normalized) against different percentage of Rh from 0 to 15 at %, without external magnetic field. This simulation is performed using inputs data of K_u , M_s and α obtained from experiments and driving current of 3.2 mA. It can be observed from the graph that when Rh increases, oscillation frequency will increase until it reaches a peak at about 21 GHz (Rh is 12%), where α is almost at the lowest (i.e. about 0.025 from FIG. 5A) and K_u remains negative (i.e. about -0.06×10^6 erg/cm³ from FIG. 3). The oscillation frequency drops drastically after 12% Rh due to the decrease in K_u (K_u becomes positive). It is clearly shown in the graph that an improvement in oscillation frequency by about 4 to 5 times (increase from about 4 to 21 GHz) is possible by using alloy $\text{Co}_{85}\text{Ir}_{(15-x)}\text{-Rh}_x$ (such as 12% Rh) as the oscillation layer, as compared to alloy CoIr (0% Rh). Further, it can also be observed from the graph that when Rh increases from 0% to 10%, the magnetic field of STO is also improved.

FIG. 7A illustrates a graph of oscillation or precession frequency against different percentage of Rh from 0 to 15 at %, in the presence of external magnetic field at 0, 2000, 4000, 6000 and 8000 Oe. FIG. 7B illustrates a graph of ac magnetic field (normalized) against different percentage of Rh from 0 to 15 at %, in the presence of external magnetic field at 0, 2000, 4000, 6000 and 8000 Oe. An external magnetic field can be perceived by STO in the write head (with reference to MAMR). It can be observed from the graphs that, in the

presence of external magnetic field, both oscillation frequency and magnetic field are deteriorating, especially at higher external magnetic field and higher percentage of Rh (where K_u is low). Therefore, K_u needs to be improved further so as to provide directionality and stability of magnetization of the oscillation layer. This can be done by optimizing the underlayers and/or heat treatment to the system. Nevertheless, regardless the presence of an external magnetic field, a STO using alloy Colr-Rh as the oscillation layer is still proved to be better than alloy Colr.

FIG. 8 illustrates a graph of magnetic moment against applied magnetic field (Oe), for Colr (0% Rh) and Colr-Rh (2% Rh). From the graphs, a reduction in the perpendicular component is clearly seen when 2% Rh is used in Colr-Rh (as Rh has a smaller atomic radii), which is beneficial for an oscillation layer operating approximately in-plane. This is because the perpendicular component would induce a positive K_u which will be detrimental to a STO using in-plane oscillation.

FIG. 9A illustrates a coercivity plot (H_c) at all angles (0 to 360 degree) with different percentage of Rh from 0 to 15 at %. FIG. 9B and 9C are two coercivity plots with an enlarge scale for the same coercivity plot as illustrated in FIG. 9A. FIG. 9B shows that with 2% Rh in Colr-Rh, the uniformity of the coercivity plot at all angles is improved from an off-circular oval shape (0% Rh) to a nearly circular shape (2% Rh). This uniformity will advantageously improve the stability of magnetization precession of STO. As shown in FIG. 9C, with more than 10% Rh in Colr-Rh, the coercivity plot becomes an off-circular shape (non-uniform) and smaller. Therefore, the coercivity may be greatly improved with only a small percentage of Rh in Colr-Rh.

FIG. 10 illustrates a graph of magnetoresistance (MR) ratio against applied magnetic field with the polarization layer made of different materials coupled to the oscillation layer. The polarization layer may be made of a magnetic material such as Co or Co/Cu/Co. The graphs show that MR ratio is improved with the presence of a polarization layer. It is shown that a polarization layer made of Co with a thickness of 0.8 nm may increase the MR ratio to 2.3%. It is also shown that a polarization layer made of a trilayer of Co 0.8nm/Cu 0.3nm/Co 0.8nm may increase the MR ratio to 3.2%. The increase in MR ratio is associated to an enhancement in spin polarization rate, which consequently improve the efficiency of STO.

A method of fabricating a STO in accordance to an embodiment of the present invention as depicted in FIG. 1 and 2 is as follow. The method comprises the steps of forming an oscillation layer for generating a high frequency magnetic field with a low driving current wherein the oscillation layer is made of an alloy $\text{Co}_{85}\text{Ir}_{(15-x)}\text{-Rh}_x$ where x is about 1 to 14 at %; forming a reference layer made of a magnetic material to induce a precession of magnetization in the oscillation layer; and forming at least one polarization layer between the oscillation layer and the reference layer to enhance spin polarization rate of the spin torque oscillator.

In one embodiment, the step of forming the at least one polarization layer comprises forming a first polarization layer and a second polarization layer. The first polarization layer is coupled to the oscillation layer to enhance spin polarization rate of the oscillation layer and the second polarization layer is coupled to the reference layer to enhance spin polarization rate of the reference layer. The method further comprises forming a spacer (made of a non-magnetic material) between the first and second polarization layers.

In one embodiment, the step of forming the oscillation layer comprises forming a first oscillation layer and a second oscillation layer. The method further comprises forming an interlayer (made of a suitable material such as Ru) between the first and second oscillation layers so as the first and second oscillation layers can be coupled ferromagnetically or anti-ferromagnetically.

The STO produced by the method as described above has the characteristics and properties as discussed in the present application and illustrated in FIG. 1 to 10.

While the present invention has been described in certain aspects and with reference to specific embodiments, it should be understood by those skilled in the art that various modifications and/or variations may be made to the invention without departing from the spirit or scope of the invention. Thus, the embodiments should be considered in all respects as illustrative and not restrictive. Accordingly, the scope of the invention should be determined by the appended claims and their equivalents which are intended to be embraced.

CLAIMS

1. A spin torque oscillator comprising:
 - an oscillation layer configured to generate a high frequency magnetic field with a low driving current wherein the oscillation layer is made of an alloy $\text{Co}_{85}\text{Ir}_{(15-x)}\text{-Rh}_x$ where x is about 1 to 14 at %;
 - a reference layer made of a magnetic material to induce a precession of magnetization in the oscillation layer; and
 - at least one polarization layer disposed between the oscillation layer and the reference layer to enhance spin polarization rate of the spin torque oscillator.
2. The spin torque oscillator of claim 1 wherein the at least one polarization layer comprising a first polarization layer and a second polarization layer wherein the first polarization layer is coupled to the oscillation layer to enhance spin polarization rate of the oscillation layer and the second polarization layer is coupled to the reference layer to enhance spin polarization rate of the reference layer.
3. The spin torque oscillator of claim 2 further comprising a spacer disposed between the first and second polarization layers wherein the spacer is made of a non-magnetic material.
4. The spin torque oscillator of claim 1 wherein the oscillation layer comprising a first oscillation layer and a second oscillation layer.
5. The spin torque oscillator of claim 4 further comprising an interlayer disposed between the first and second oscillation layers so that the first and second oscillation layers are coupled ferromagnetically or anti-ferromagnetically.
6. The spin torque oscillator of claim 5 wherein the interlayer is made of Ru having a thickness of about 1.6 to 2.4 nm such that the first and second oscillation layers are coupled ferromagnetically.
7. The spin torque oscillator of claim 5 wherein the interlayer is made of Ru having a thickness of about 0.6 to 1.2 nm such that the first and second oscillation layers are coupled

anti-ferromagnetically.

8. The spin torque oscillator of claim 1 wherein the least one polarization layer is made of Co having a thickness of about 0.5 to 1.0 nm.
9. The spin torque oscillator of claim 1 wherein the at least one polarization layer is made of a trilayer of Co/Cu/Co having a thickness of about 0.5 to 0.8 nm/ 0.2 to 0.5 nm/ 0.5 to 0.8 nm.
10. The spin torque oscillator of claim 1 wherein the oscillation layer having an anisotropy energy density (k_u) of about $-(0.5 \text{ to } 10) \times 10^6 \text{ erg/cm}^3$.
11. The spin torque oscillator of claim 1 wherein the oscillation layer having a damping constant (α) of about 0.01 to 0.15.
12. The spin torque oscillator of claim 1 wherein the oscillation layer having a saturation magnetization (M_s) of about 800 to 1200 emu/cm³.
13. The spin torque oscillator of claim 1 wherein the high frequency magnetic field generated by the oscillation layer is about 500 to 1500 Oe.
14. The spin torque oscillator of claim 1 wherein the driving current is about 1 to 5 mA.
15. The spin torque oscillator of claim 1 wherein the least one polarization layer having a spin polarization rate of about 0.3 to 0.55.
16. The spin torque oscillator of claim 1 wherein the least one polarization layer having a damping constant of about 0.01 to 0.02.
17. The spin torque oscillator of claim 1 wherein the reference layer having an anisotropy energy density (k_u) of about $(0 \text{ to } 1) \times 10^7 \text{ erg/cm}^3$.
18. The spin torque oscillator of claim 1 wherein the reference layer having a saturation magnetization (M_s) of about 500 to 1000 emu/cm³.

19. The spin torque oscillator of claim 1 wherein the reference layer having a magnetic anisotropy axis in a direction in-plane or perpendicular to the oscillation layer.
20. The spin torque oscillator of claim 1 wherein the reference layer having a thickness of about 10 to 20 nm.
21. The spin torque oscillator of claim 1 wherein the oscillation layer having a thickness of about 10 to 20 nm.
22. The spin torque oscillator of claim 4 wherein the first oscillation layer having a thickness of about 5 to 10 nm.
23. The spin torque oscillator of claim 4 wherein the second oscillation layer having a thickness of about 5 to 10 nm.
24. A method of fabricating a spin torque oscillator comprising:
forming an oscillation layer for generating a high frequency magnetic field with a low driving current wherein the oscillation layer is made of an alloy $\text{Co}_{85}\text{Ir}_{(15-x)}\text{-Rh}_x$ where x is about 1 to 14 at %;
forming a reference layer made of a magnetic material to induce a precession of magnetization in the oscillation layer; and
forming at least one polarization layer between the oscillation layer and the reference layer to enhance spin polarization rate of the spin torque oscillator.
25. The method of claim 24 wherein the step of forming the at least one polarization layer comprising forming a first polarization layer and a second polarization layer wherein the first polarization layer is coupled to the oscillation layer to enhance spin polarization rate of the oscillation layer and the second polarization layer is coupled to the reference layer to enhance spin polarization rate of the reference layer.
26. The method of claim 25 further comprising forming a spacer between the first and second polarization layers wherein the spacer is made of a non-magnetic material.

27. The method of claim 24 wherein the step of forming the oscillation layer comprising forming a first oscillation layer and a second oscillation layer.

28. The method of claim 27 further comprising forming an interlayer between the first and second oscillation layers so that the first and second oscillation layers are coupled ferromagnetically or anti-ferromagnetically.

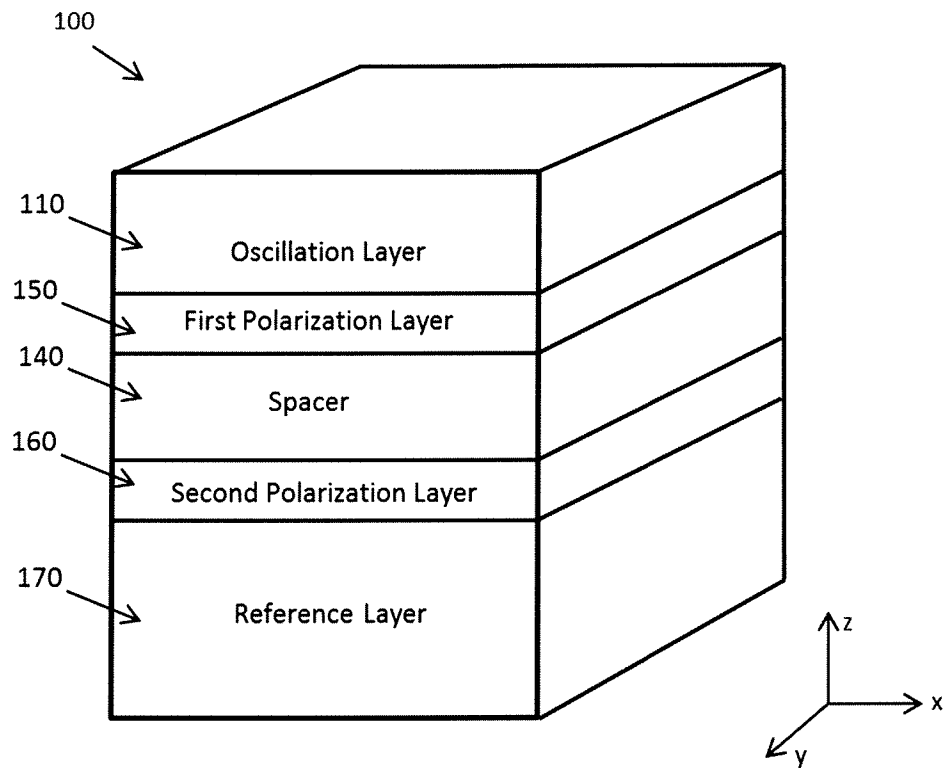


FIG. 1

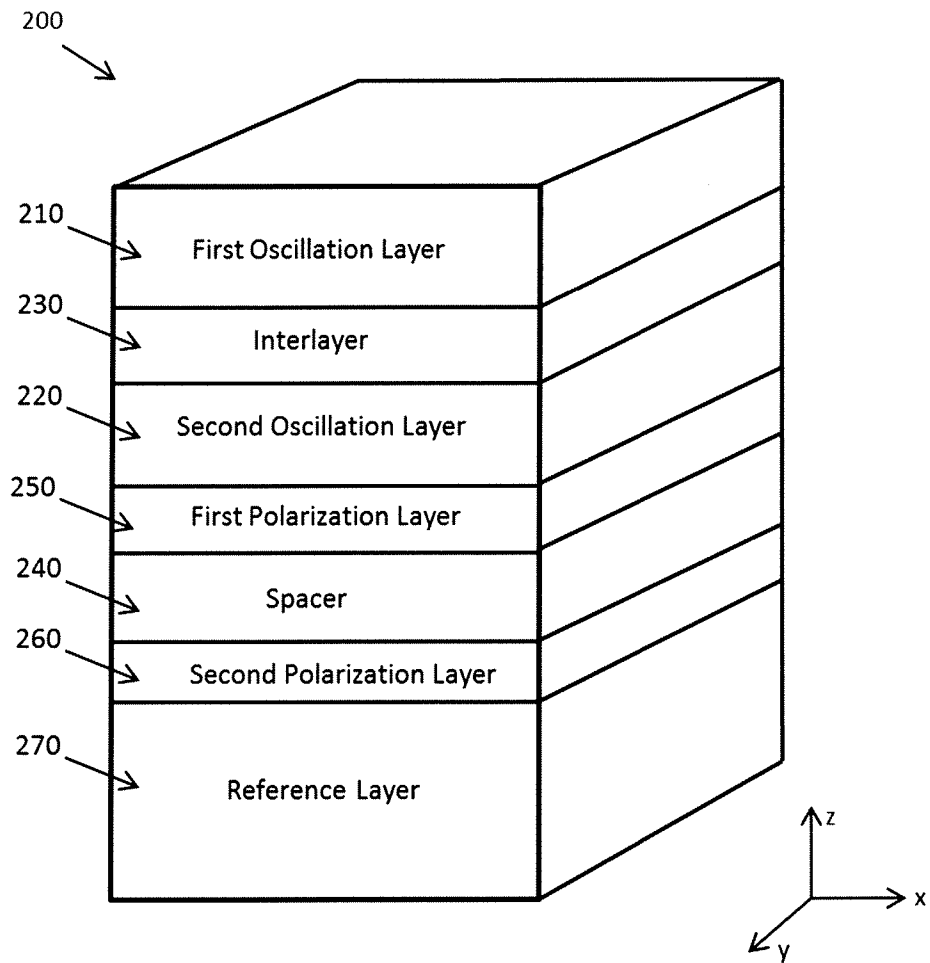


FIG. 2

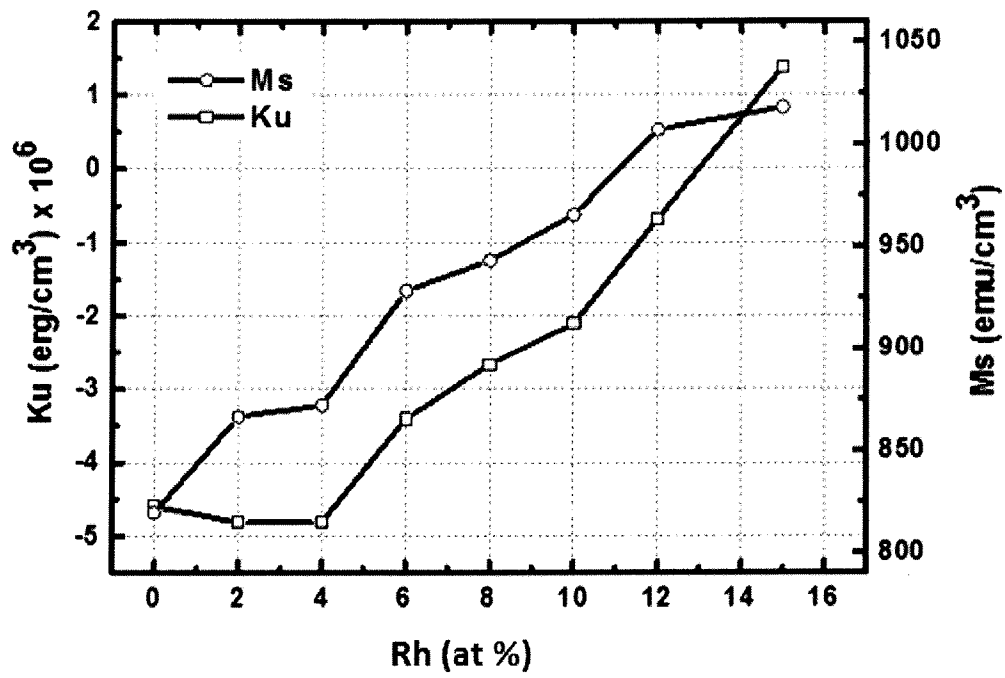


FIG. 3

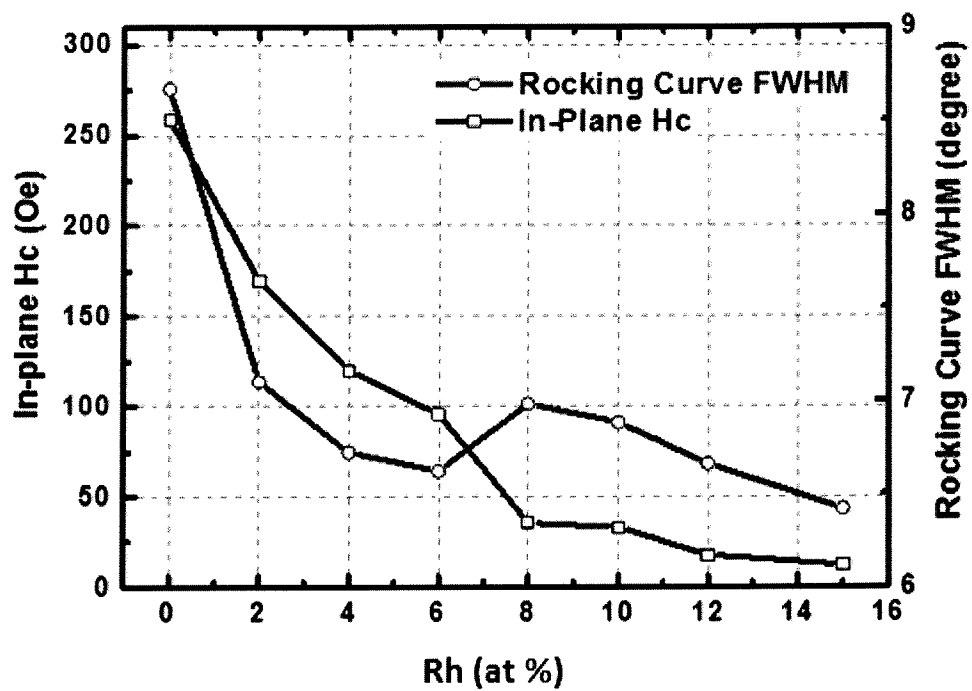


FIG. 4

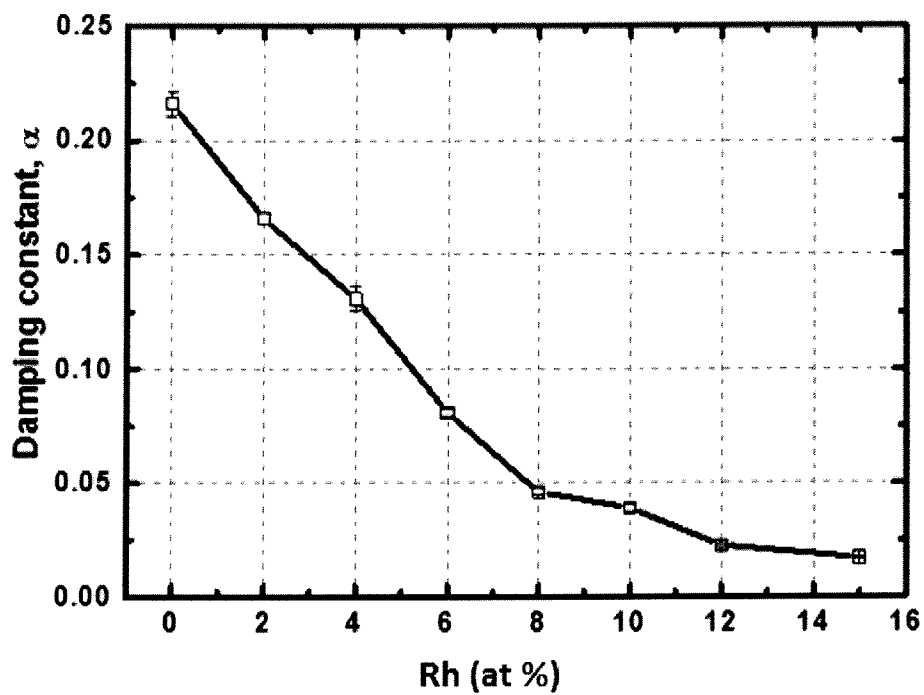


FIG. 5A

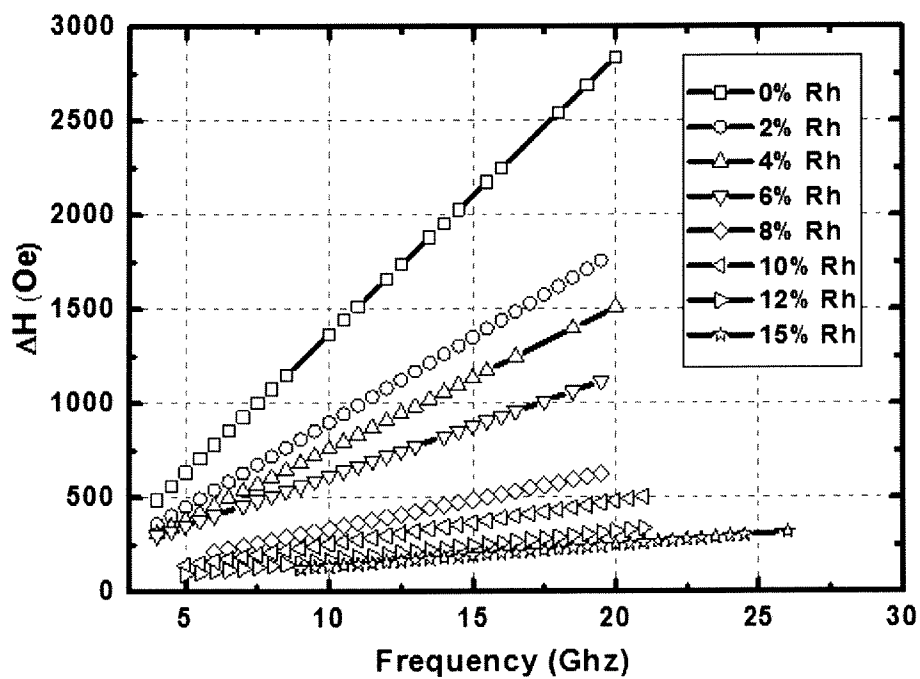


FIG. 5B

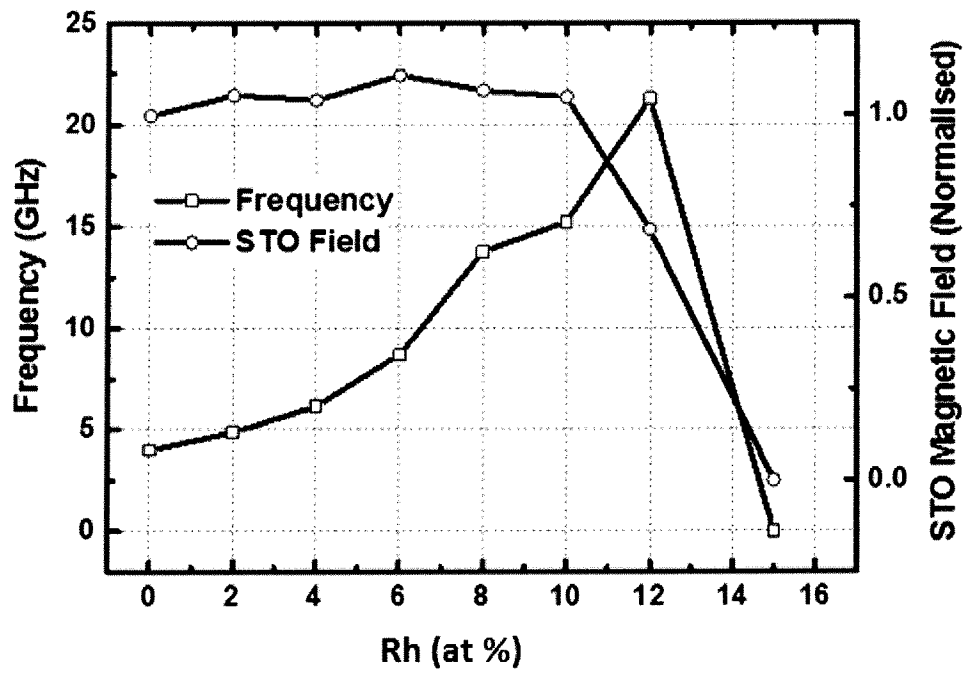


FIG. 6

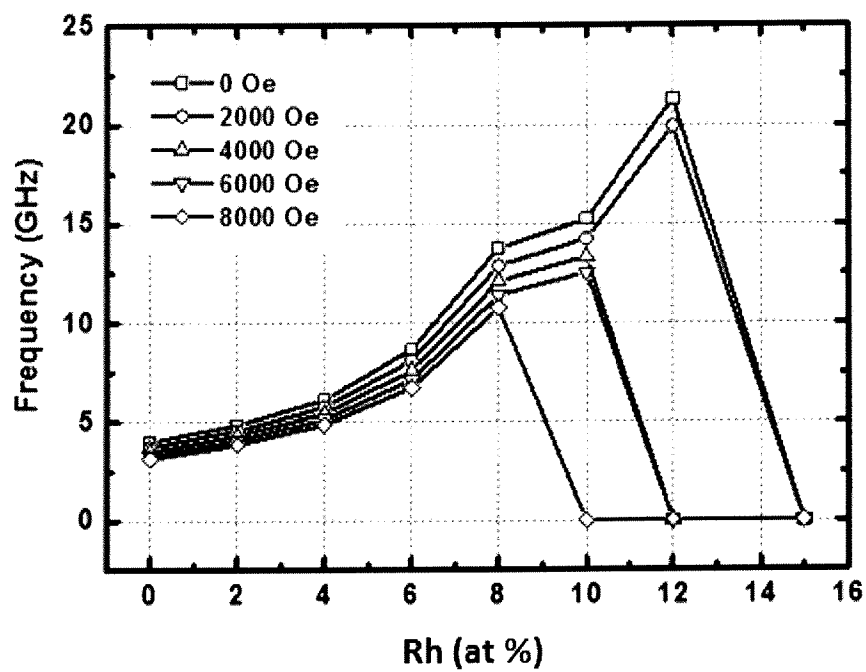


FIG. 7A

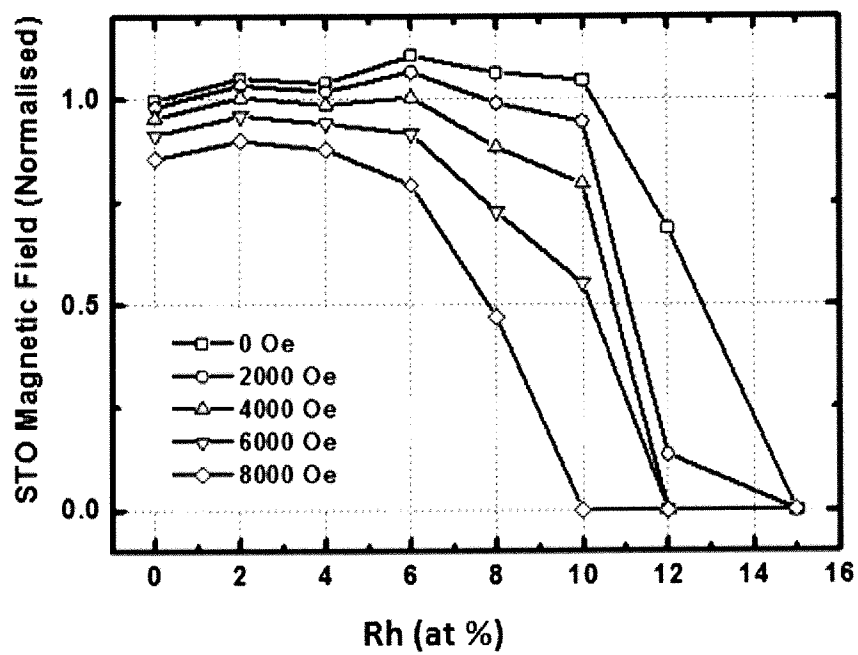


FIG. 7B

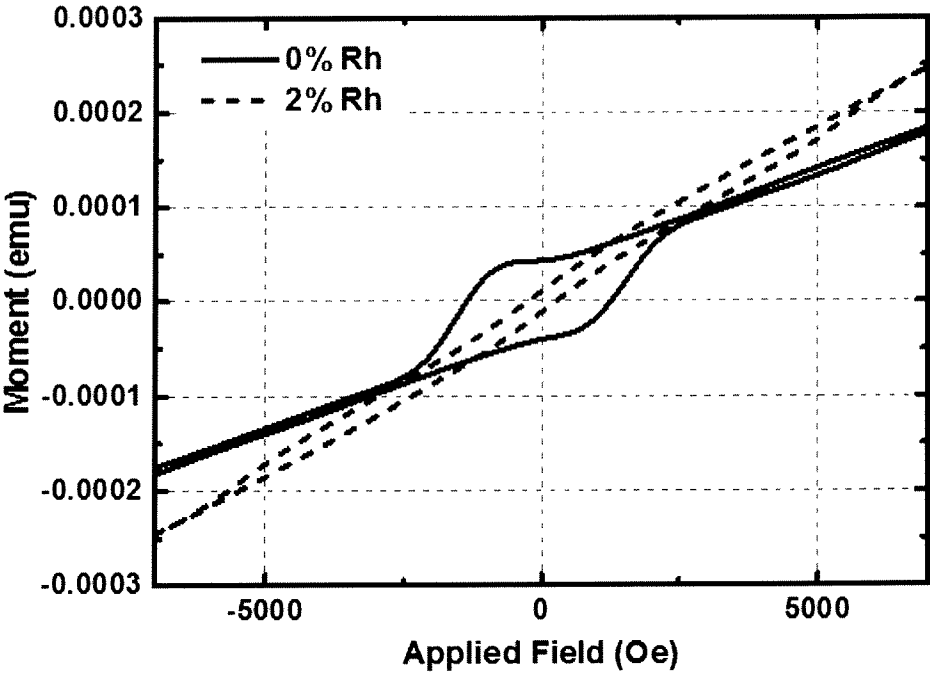


FIG. 8

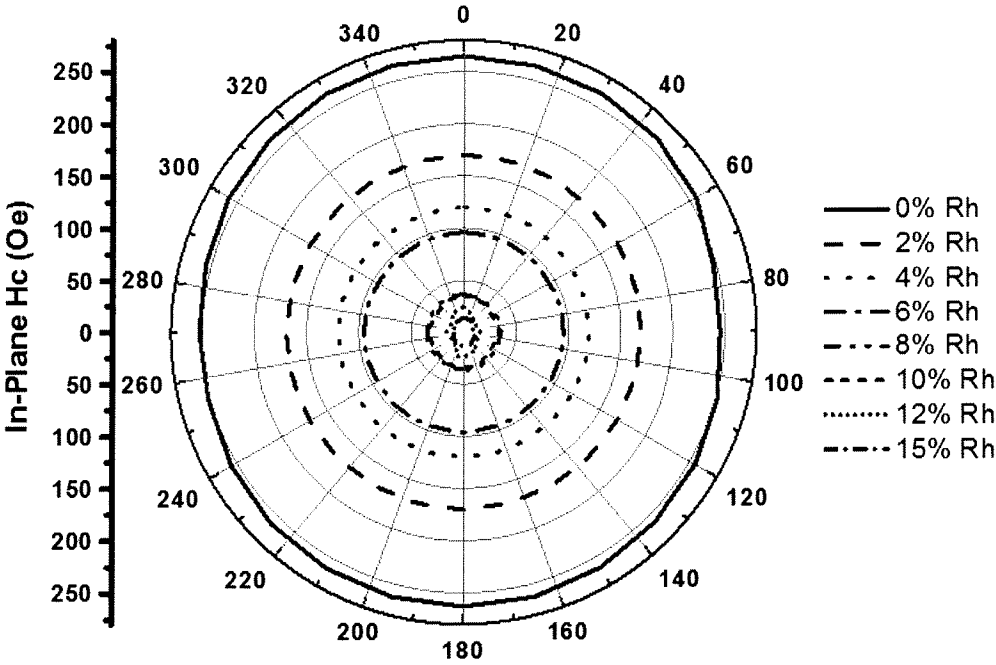


FIG. 9A

10/11

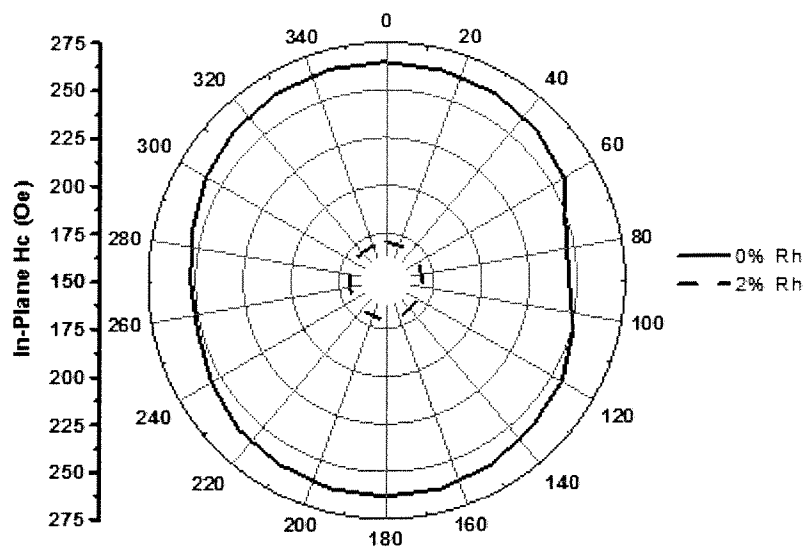


FIG. 9B

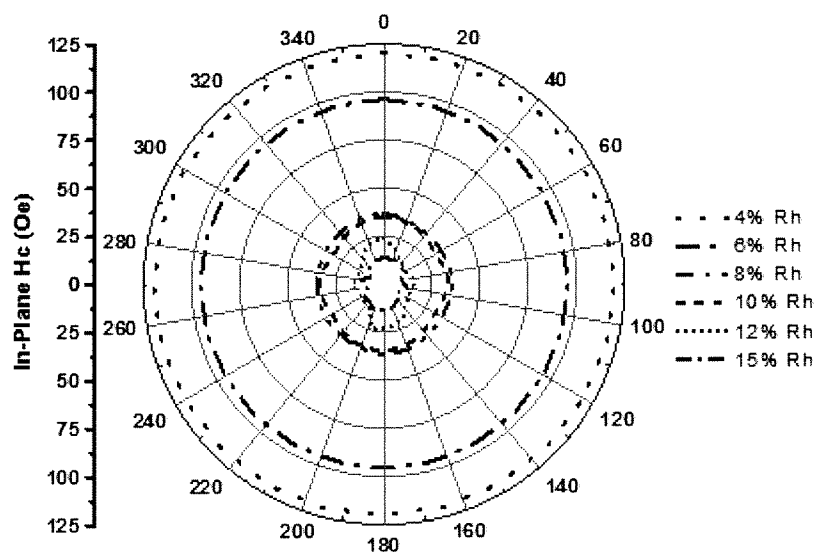


FIG. 9C

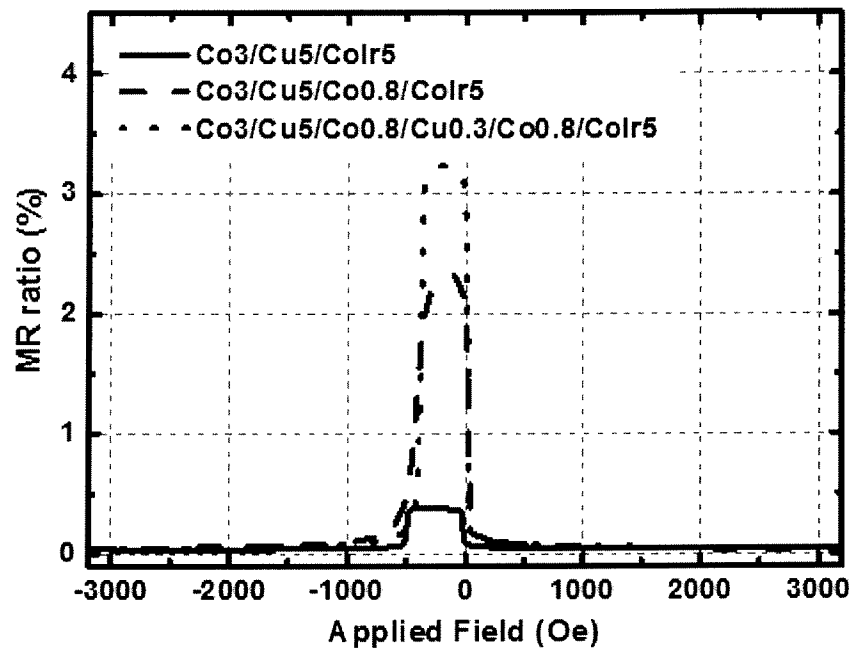


FIG. 10

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2015/050448

A. CLASSIFICATION OF SUBJECT MATTER

See Supplemental Box

According to International Patent Classification (IPC)

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H01F, H01L, C22C, G11B, H01F

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, WPI, PAJ, FULLTEXT, SCOPUS; synonyms, variations and combinations of: spin, torque, oscillator, microwave assisted magnetic recording, layer, cobalt, iridium, rhodium.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2011/0255197 A1 (TSUCHIYA Y. ET AL) 20 October 2011 Paras [0052] & [0055-0056]; Fig 1	1-28
A	US 2014/0139952 A1 (TAKEO A. ET AL) 22 May 2014 Paras [0026] & [0054] Fig 1	1-28
A	US 2012/0242438 A1 (MORISE H. ET AL) 27 September 2012 Paras [0003], [0029-0034], [0118-0119], [0124-0129] & [0135]; Figs 1A, 1B, 5A, 5B & 6	1-28

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

☒ See patent family annex.

*Special categories of cited documents:

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

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

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

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search

04/01/2016

(day/month/year)

Date of mailing of the international search report

12/01/2016

(day/month/year)

Name and mailing address of the ISA/SG



Intellectual Property Office of Singapore
51 Bras Basah Road
#01-01 Manulife Centre
Singapore 189554

Email: pct@ipos.gov.sg

Authorized officer

Sreekanth Purushotham

IPOS Customer Service Tel. No.: (+65) 6339 8616

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2015/050448

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2011/0064969 A1 (CHEN E. Y. ET AL) 17 March 2011 Paras [0005], [0052] & [0068]; Fig 4C	1-28
A	US 2013/0069185 A1 (SAIDA D. ET AL) 21 March 2013 Paras [0033-0039], [0055] & [0113]; Figs 1A & 1B	1-28
A	US 2013/0077388 A1 (INOKUCHI T. ET AL) 28 March 2013 Para [0023-0024]; Figs 1 & 2	1
A	US 2009/0015958 A1 (NAKAMURA S. ET AL) 15 January 2009 D5 Paras [0036-0039] & [0070]; Fig 1	1-28
A	US 2009/0213638 A1 (MORISE H. ET AL) 27 August 2009 Para [0112]	1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/SG2015/050448

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2011/0255197 (A1)	20/10/2011	US 8279548 (B2)	02/10/2012
US 2014/0139952 (A1)	22/05/2014	US 8837087 (B2) JP 2014-103172 (A)	16/09/2014 05/06/2014
US 2012/0242438 (A1)	27/09/2012	US 8569852 (B2) JP 2012-204682 (A) JP 5321851 (B2)	29/10/2013 22/10/2012 23/10/2013
US 2011/0064969 (A1)	17/03/2011	US 8072800 (B2) CN 104009154 (A) KR 20140107143 (A) TW 201444135 (A) US 2012/0075927 (A1) US 8456898 (B2) US 2013/0177781 (A1) US 9082534 (B2)	06/12/2011 27/08/2014 04/09/2014 16/11/2014 29/03/2012 04/06/2013 11/07/2013 14/07/2015
US 2013/0069185 (A1)	21/03/2013	US 8716817 (B2) JP 2013-069820 (A) JP 5767925 (B2)	06/05/2014 18/04/2013 26/08/2015
US 2013/0077388 (A1)	28/03/2013	US 8958239 (B2) JP 2013-073978 (A) JP 5711637 (B2) KR 20130033276 (A) KR 101375389 (B1)	17/02/2015 22/04/2013 07/05/2015 03/04/2013 17/03/2014
US 2009/0015958 (A1)	15/01/2009	US 8085582 (B2) JP 2009-021352 (A) JP 4874884 (B2) US 2012/0061784 (A1) US 8611142 (B2) US 2014/0078807 (A1)	27/12/2011 29/01/2009 15/02/2012 15/03/2012 17/12/2013 20/03/2014
US 2009/0213638 (A1)	27/08/2009	US 7889543 (B2) JP 2009-200216 (A) JP 5455313 (B2)	15/02/2011 03/09/2009 26/03/2014

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2015/050448

Supplemental Box

(Classification of Subject Matter)

Int. Cl.

H01F 10/32 (2006.01)

H01L 29/66 (2006.01)

C22C 19/07 (2006.01)

G11B 5/00 (2006.01)

H01F 10/12 (2006.01)