



(51) International Patent Classification:
G11B 5/66 (2006.01)

(21) International Application Number:
PCT/US2014/071625

(22) International Filing Date:
19 December 2014 (19.12.2014)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
14/136,615 20 December 2013 (20.12.2013) US

(71) Applicant: SEAGATE TECHNOLOGY LLC [US/US];
10200 South De Anza Boulevard, Cupertino, CA 95014
(US).

(72) Inventors: KIM, Jai-Young; 1109 Hoskins Lane, San Ramon, CA 94582 (US). MORKVED, Terry, Lee; 38401 Paseo Padre PKWY, Fremont, CA 94536 (US). NOLAN, Thomas, P.; 279 E. Warren Avenue, Fremont, CA 94539 (US). LU, Bin; 1186 Bellingham Sq., San Ramon, CA 94582 (US). LEE, Li-lien; 13451 Ward Way, Saratoga, CA 95070 (US). LI, Pengcheng; 300 Aleut Ct., Fremont, CA 94539 (US).

(74) Agent: MCCARTHY, Randall, K.; Hall Estill Attorneys at Law, 100 North Broadway, Suite 2900, Oklahoma City, OK 73102 (US).

(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: PERPENDICULAR MAGNETIC RECORDING MEDIUM WITH LOW EXCHANGE COUPLING

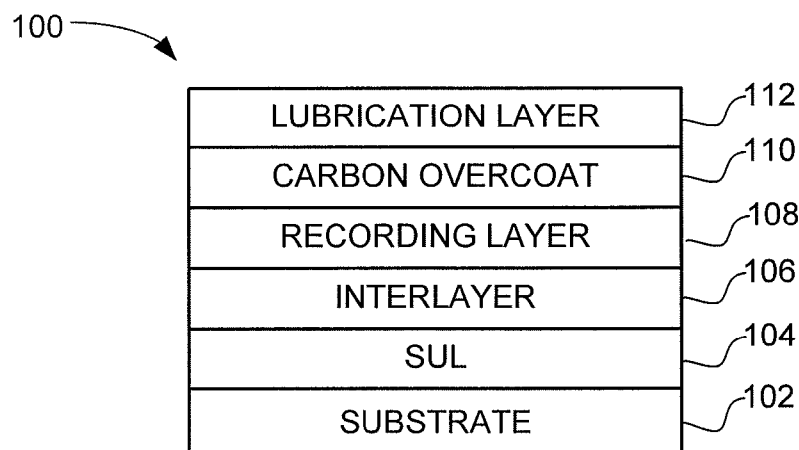


FIG. 1

(57) Abstract: A perpendicular magnetic recording medium (100) having a recording layer (108) with low exchange coupling. In some embodiments, the perpendicular magnetic recording medium is provided with a granular magnetic recording layer (114) comprising an alloy of cobalt (Co), platinum (Pt) and a platinum group metal element to decrease intra-layer exchange coupling between adjacent grains.

PERPENDICULAR MAGNETIC RECORDING MEDIUM WITH LOW EXCHANGE COUPLING

Summary

Various embodiments of the present disclosure are generally directed to a perpendicular magnetic recording medium having a recording layer with low magnetic exchange coupling.

5 In some embodiments, a perpendicular magnetic recording medium is provided with a granular magnetic recording layer comprising an alloy of cobalt (Co), platinum (Pt) and a platinum group metal element to decrease intra-layer exchange coupling between adjacent grains.

10 In other embodiments, a perpendicular magnetic recording medium has a granular magnetic recording layer with magnetic grains surrounded by a non-magnetic material, the recording layer formed of a CoPtRh alloy, the Rh decreasing intra-layer exchange coupling between adjacent grains.

15 These and other features and advantages of various embodiments can be understood with a review of the following detailed description and the accompanying drawings.

Brief Description of the Drawings

FIG. 1 is an example perpendicular magnetic recording medium in accordance with various embodiments of the present disclosure.

20 FIG. 2 is an example multi-layer recording layer structure of the medium of FIG. 1.

FIG. 3A is a graphical representation of magnetic coercivity (H_c) v. a magnetic saturation parameter for exemplary storage media.

25 FIG. 3B is a graphical representation of magnetization field (H_n) strength v. the magnetic saturation parameter for the exemplary storage media.

FIG. 4 is a graphical representation of slope data for magnetic hysteresis loops for the exemplary storage media.

-2 -

FIG. 5A is a graphical representation of full width half maximum (FWHM) data for the exemplary storage media.

FIG. 5B is a graphical representation of further FWHM data for the exemplary storage media.

5 FIG. 6 is a graphical representation of further FWHM data for the exemplary storage media.

FIG. 7 is a graphical representation of high frequency amplitude (HFA) data for the exemplary storage media.

10 FIG. 8A is a graphical representation of recording density in kilobytes per inch (KBPI) for the exemplary storage media.

FIG. 8B is a graphical representation of recording density in kilotracks per inch (KTPI) for the exemplary storage media.

FIG. 8C shows the data of FIG. 8B with greater resolution.

15 FIG. 9 is a graphical representation of reverse overwriting performance metrics for the exemplary storage media.

FIG. 10A is a graphical representation of areal density capability data for the exemplary storage media.

FIG. 10B shows the data of FIG. 10A with greater resolution.

20 FIG. 11 is a graphical representation of side track erase loss data for the exemplary storage media.

FIG. 12 is a graphical table showing various parameters of the exemplary storage media.

FIG. 13 is a graphical representation of perpendicular magnetic anisotropy (Hk) data for further exemplary storage media.

25 FIG. 14 is a graphical representation of further Hk data for the further exemplary storage media.

FIG. 15 is a graphical representation of HCP fraction data for the further exemplary storage media.

30 FIG. 16 is a graphical representation of Hk data for the further exemplary storage media.

-3 -

FIG. 17 is a graphical representation of further HCP fraction data for the further exemplary storage media.

FIG. 18 is a graphical representation of track pitch data for the further exemplary storage media.

5

Detailed Description

Perpendicular recording media are commonly employed in state-of-the-art magnetic recording systems. Perpendicular recording media have a perpendicular anisotropy (H_k) in a magnetic layer and magnetization formed in a direction to the surface of the magnetic layer. Typically, perpendicular recording media are often fabricated with polycrystalline cobalt-platinum (CoPt) and cobalt-platinum-chromium (CoPtCr) alloys. Co-rich areas in the polycrystalline film are ferromagnetic while Cr and/or oxide rich areas in the film are non-magnetic. Magnetic interactions between adjacent ferromagnetic grains are attenuated by the non-magnetic areas in between.

High density perpendicular recording media require carefully balanced magnetic properties including: high enough anisotropy to ensure thermal stability, resist erasure, and function effectively with modern head designs; low enough switching field to enable writability by the head; low enough lateral exchange coupling to maintain small correlation length between magnetic grains or clusters; high enough lateral exchange coupling to maintain a narrow switching field distribution (SFD); and grain-to-grain uniformity of magnetic properties sufficient to maintain thermal stability and minimum SFD.

As recording density continues to increase, it is necessary to make smaller grain structures both laterally to maintain the number of magnetic particles in a bit at a smaller value, and vertically to minimize the effective head-to-media spacing. Smaller grain structures are easier to erase, requiring higher moment (M_s) to maintain signal and higher anisotropy field (H_k) to maintain thermal stability. Such high K_u materials are difficult to manufacture with all of the desired properties for either granular oxide containing or metallic layers required for modern perpendicular recording layer structures.

30

-4 -

High Pt% required to provide the high H_k is limited by the promotion of stacking faults that begin to reduce the H_k, particularly in combination with common segregating exchange reduction materials such as Boron. High Co% used to form high M_s materials also increases the exchange stiffness and thus exchange coupling to the detriment of recording performance. Thus, there is a continuing and increasing need in the art for magnetic recording layers that maintain the desired media microstructures while employing high Pt% to increase H_k and M_s without substantially increasing lateral exchange coupling or incorporation of stacking faults that degrade anisotropy and uniformity of properties.

Cobalt-based "Co-alloys" have been the thin-film magnetic recording media material of choice for about 30 years owing to their unique magnetic nature and HCP structure giving high uniaxial anisotropy. It is well known that addition of Pt up to about 25% raises anisotropy significantly, until it increases the c/a ratio of lattice parameters sufficiently to promote stacking faults to form regions of fcc structure that has multiple magnetic easy axes and very low anisotropy. It is further known that the exchange stiffness and corresponding exchange coupling between densely packed grains increases with magnetic moment and with anisotropy. It is also a quantum mechanical interaction that depends on the interaction between neighboring magnetic atoms, and so depends on Co concentration in the alloy. Exchange between Co atoms is also significantly higher than for other magnetic atoms such as Fe and Ni. Thus, pure Co has very high innate intergranular exchange coupling, and CoPt alloys are even higher, owing to the anisotropy increase.

Non(ferro)magnetic materials such as chromium (Cr) and boron (B) have been added to reduce the moment, and thereby exchange and demagnetization effects.

Unfortunately, these materials also lower the amount of Pt that can be added without faulting, and the maximum H_k and K_u that can be achieved. It has been further proposed to add hcp stabilization materials such as ruthenium (Ru) to increase the resistance to stacking faults. This further reduces M_s and thus K_u as well as exchange coupling. In general, it has been found that modern magnetic recording layers employ an average M_s of about 400-600 emu/cc along with a well established variety of grain

-5 -

boundary segregation methods to obtain the optimum decoupling. There have been many efforts to increase the Ms of the recording layer to enable thinner and higher anisotropy designs that reduce spacing losses. However, it has been consistently found that the increased Co% and increased Pt% for high moment and high anisotropy cause too much exchange coupling and too many stacking faults.

Accordingly, at least some embodiments of the present disclosure are generally directed to perpendicular recording media having recording layers formed from magnetic alloys in novel combinations so as to target an HCP Co-alloy perpendicular recording media layer having a novel magnetic property combination of higher Ku and lower exchange stiffness than prior art Co-alloy recording layers. Such embodiments can provide nominally the same Hk, Ms and Ku as prior art conventional alloys, but with lower Co concentrations to provide lower innate exchange coupling.

As explained below, some embodiments include recording layers formed of an alloy of cobalt (Co), platinum (Pt) and a platinum group metal element such as ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os) or iridium (Ir). Other embodiments include recording layers formed of an alloy of Co, Pt, Cr and Rh. Further embodiments include the addition of boron (B), iron (Fe) or nickel (Ni).

FIG. 1 is an example perpendicular recording medium 100 in accordance with various embodiments. The example medium 100 includes a substrate 102, soft magnetic underlayer (SUL) 104, interlayer 106, recording layer 108, carbon overcoat (COC) layer 110 and lubricant layer 112. Other configurations can be used so that the example medium is merely illustrative and not limiting. The recording layer 108 can be a single layer or multiple layers, such as represented by recording layers 114, 116 and 118 in FIG. 2.

In some embodiments, the intermediate layer 116 is a magnetic recording layer. In other embodiments, the intermediate layer 116 is a non-magnetic exchange break (EB) layer. The various formulations discussed below can be applied to these and other types of recording layers. The layers may take various forms including continuous granular composite (CGC) structures.

-6 -

A first embodiment will now be discussed that generally uses an alloy of Co, Pt and a platinum group metal element for one or more of the recording layers. Magnetic exchange decoupling is enhanced by the addition of the platinum group metal element into a magnetic CoPt portion, which is surrounded by a non-magnetic oxide grain boundary in a granular perpendicular magnetic recording (PMR) media. It has been found that the additional element provides substantially no degradation of crystallographic and magnetic properties of the recording layer.

As will be appreciated, controlling magnetic exchange decoupling within a granular PMR medium is important to improve dynamic recording performance, such as bit error rate (BER) and side track erase (STE) metrics. Some recording media such as 100 in FIG. 1 use a CGC structure with a granular bottom magnetic recording layer, an intermediate EB layer and a continuous top layer. The EB layer is provided to implement the concept of an exchange coupled composite (ECC) structure.

To improve the PMR performance, the bottom and top layers tend to be fully exchange decoupled and adjustably exchange coupled, respectively, to optimize the supplied magnetic recording head field gradient. Physical and chemical sputtering methods have been used in the art to obtain the requisite columnar grain structure and oxide grain boundary structures.

Physical exchange decoupling by using a columnar grain structure can be implemented using high pressure sputtering deposition. For the columnar structure in PMR media, the crystallographic interlayer (CI) beneath the bottom magnetic recording layer (e.g., interlayer 108, FIG. 1) may be deposited in a high sputtering pressure in the range of about 20 to 200 mTorr to form the crystallographic columnar grain structure. The bottom magnetic recording layer (e.g., layer 114, FIG. 2) is subsequently deposited on the columnar CI in the foregoing sputtering pressure range continuously to form the magnetic columnar structure. Voids physically separated around the magnetic columnar grain structure enhance the magnetic exchange decoupling.

Chemical exchange decoupling using an oxide grain boundary structure can be formed by reactive oxygen sputtering and/or by incorporating oxides in the sputtering

-7 -

targets. Such processing is applied to the CI, such as a (002) Ru layer, to form epitaxial grain growth for the core magnetic recording elements, such as (002) Co, (002) CoCr, (002) CoCrPt, etc. and to form oxide grain boundaries around the core magnetic elements. The boundaries chemically separated around the core elements play the role to enhance the magnetic exchange decoupling in the PMR media.

While physical and chemical exchange decoupling techniques are operable to improve PMR recording performance, limitations have been found to be associated with such techniques. The higher pressure sputtering method to generate columnar structures tends to induce various defects such as argon (Ar) gas incorporation, blisters, poor mechanical performance, corrosion points, etc. The higher content reactive sputtering method to generate oxide grain boundary structures can similarly induce particulate contamination, blisters, steep performance gradients, sputtering arcing, etc.

Accordingly, some embodiments enhance exchange decoupling by introducing a third element into the magnetic core CoPt portions. Because these portions are the original source of very strong magnetic exchange coupling in PMR media, it has been found that adding one or more platinum group elements such as Ru, Rh, Pd, Os or Ir to the magnetic core portions can lower exchange coupling within the layer without otherwise significantly affecting recording performance.

To evaluate the effects of such modifications, two types of media were formed: Type A and Type B. The two media used the same granular structure and same full PMR media structure as set forth in FIGS. 1-2. The difference between the respective media types related to the construction of the bottom granular recording layer 114; in Type A, the core magnetic portions were formed of CoPt. In Type B, the core magnetic portions were formed of CoPtRh, with the Rh substituted for a portion of the Co in the Type B media.

The Type A media used about 70-85 at.% Co and about 15-30% Pt. The Type B media used about 10% Rh, about 60-75% Co and about 15-30% Pt. In one embodiment, some Type A media was formed of about 77.5 at.% Co and 22.5 at.% Pt, and some Type B media was formed of about 10% Rh, 67 at.5% Co and 22.5 at.% Pt.

-8 -

The saturation magnetization (M_s) of the granular structure type bottom exchange decoupled magnetic layer in both the Type A and Type B media was in the range of about 610-625 emu/cc. Because the saturation magnetization values were similar, the thickness effects of the core magnetic parts in both Type A and Type B were evaluated using a combined metric M_{st} formed in relation to the saturation magnetization M_s and magnetic layer thickness T of the full structure PMR media (see FIG. 2). The nominal thicknesses of the granular structure bottom layers in both types ranged from about 65 Å to about 100 Å. The M_{st} in both types of media was linearly changed from 0.75 to 1.02 Kerr rotation angles. As a result, the M_{st} variations in the full PMR media were regarded as the proportional variation in thicknesses of the granular bottom layer.

FIGS. 3A and 3B respectively show the magnetic coercivity (H_c) and nucleation field (H_n) of the Type A media (represented by open circles throughout) and of the Type B media (represented by closed circles throughout). Generally, it was found that the magnetic coercivity H_c exhibited similar line gradients in FIG. 3A. The nucleation field (H_n), however, was about 200 Oe lower for the Type B media as compared to Type A. This implies that the direct addition of Rh into the core magnetic portions improves the magnetic exchange decoupling in the full structure granular PMR media.

To evaluate magnetic exchange decoupling, a slope value α for the magnetic hysteresis loops in the second quarter can be defined as:

$$\alpha = H_c / (H_c - H_n) \quad (1)$$

Generally, if $\alpha=1$, the PMR media is fully exchange decoupled. If $\alpha>1$, then the PMR media exhibits some exchange coupling in relation to the magnitude of the slope value. As can be seen from FIG. 4, the Type B media exhibit lower slope values (e.g., in the range of about $\alpha = 1.50$) as compared to the Type A media (e.g., in the range of about $\alpha = 1.60$). This reduction in slope indicates that the addition of Rh into the CoPt

-9 -

core effectively suppresses at least some of the magnetic exchange coupling component in the core using the same oxide grain boundary condition.

FIGS. 5A and 5B illustrate full width half maximum (FWHM) performance of an Ru underlayer (e.g., layer 116, FIG. 2) and a Co magnetic recording layer (e. g., layer 118, FIG. 2) via x-ray diffraction (XRD) curves for the Type A (open circles) media and the Type B (closed circles) media. It is observed that the addition of the Rh does not significantly degrade the crystallographic arrangement of the PMR media for all evaluated thickness ranges, since both the Ru FWHM and the Co FWHM are located around 2.48 to about 2.52 degrees and around 2.80 to about 2.90 degrees, respectively for both media types. This indicates that the crystallographic qualities of the Type A and Type B media are substantially equivalent.

FIG. 6 graphically illustrates the delta (difference) in the FWHM values between the Ru interlayer and the Co magnetic layer for both Type A (open circles) and Type B (closed circles). For all evaluated thicknesses, the delta FWHM tended to substantially reside a range of from about 0.3 to about 0.4 degrees. This indicates that both Type A and Type B media maintain the (002) textured hetero epitaxial growth relationship between the bottom interlayer and top magnetic layer, regardless of the addition of the Rh into the CoPt core. Based on the foregoing, it may be concluded that the use of CoPtRh core magnetic parts in the granular media have substantially no deleterious effect on crystallographic and interface quality, and at the same time serve to enhance exchange decoupling.

FIG. 7 graphically shows electric signal high frequency amplitude (HFA) performance for the Type A (open circles) and Type B (closed circles) media. From FIG. 7 it can be seen that the Type B media exhibits higher HFA as compared to the Type A media, which further indicates better exchange decoupling. Greater decoupling and HFA is demonstrated for greater thicknesses of the Type B media, with a peak value above 11.25 as Mst approaches 1.00. The Type B media further shows a slower decrease beyond the peak value as compared to the Type A media as thickness continues to increase.

-10 -

FIG. 8A shows recording bit densities in terms of kBPI (kilo bits per inch) for the respective Type A (open circles) and Type B (closed circles) media, and FIG. 8B shows recording track densities in terms of kTPI (kilo tracks per inch) for the respective media. FIG. 8C shows a portion of the data from FIG. 8B with greater y-axis resolution. It will be appreciated that the kBPI metric generally relates to data recording density in the direction of recording (e.g., downtrack direction) which extends circumferentially around the medium (rotatable disc). The kBTI metric generally relates to data recording density in a radial direction with respect to the medium (cross track direction).

As the magnetic layer thickness increases, the Type A media monotonically decreases the bit densities due to the increase of the transition jitter noise which is mainly attributed to the higher levels of magnetic exchange coupling in the media. The type B media increases the bit densities up to a level of about $Mst=0.85$, and then slowly decreases for thicknesses about this ratio.

The changes in the recording bit densities in both media types from FIGS. 8A-8C are consistent with the slope data in FIG. 4 and the HFA response in FIG. 7, indicating enhanced decoupling by the Type B media. With respect to the recording track densities, the track densities generally increase linearly with increases in layer thickness (e.g. Mst), which corresponds to the H_c data shown in FIG. 3. For the thicker $Mst=1$ media range, the Type A media demonstrates relatively poor track density values, which appear to be related to the low reverse overwriting (R-OW) capabilities of the media. The Type B media maintains higher track density values with similar H_c .

It is believed that the high coercivity recording bits are strongly bonded due to the higher exchange coupling in the Type A media, making it difficult to reverse the recording bits under a given magnetic recording head field strength and gradient in the Type A media. The Type B media allows the reversal of the recording bits in an easier fashion using the same field strength and gradient.

FIG. 9 demonstrates reverse overwriting performance (in dB) of the Type A (open circles) and Type B (closed circles) media. As noted above, reverse overwriting

- 11 -

relates to the ability of the magnetic write element to record a new magnetization pattern to the PMR media, which will tend to reverse at least portions of the previous magnetization state. A lower reverse overwriting (REV-OW) value tends to indicate easier (better) writability of the PMR media.

5 It can be seen from FIG. 9 that for thicknesses corresponding to an Mst of up to around 0.85, both media types exhibit good REV-OW performance. Beyond an Mst of 0.85, both media types increase REV-OW but at different rates, with the Type B media exhibiting better overwrite characteristics as compared to the Type A media.

10 It is believed that the large magnetic clusters with higher exchange coupling in the Type A media resist the magnetic reversal of the recording bits under a given magnetic recording head field and gradient, resulting in lower kBPI and kTPI performance for the Type A media as demonstrated in FIGS. 8A-8C, and the noisier performance of the Type A media as demonstrated in FIG. 7. Accordingly, the addition of the Rh in the Type B media further enhances writeability of the PMR
15 media, particularly for greater recording layer thicknesses.

FIG. 10A is a graphical representation of relative areal density capability for the Type A (open circles) and Type B (closed circles) media. FIG. 10B shows a portion of the data from FIG. 10A in greater detail. It will be appreciated that the areal density data in FIG. 10A is correlated to the downtrack (kBPI) and cross track (kTPI)
20 data from FIGS. 8A-8C. Both media types exhibit peak areal density capabilities, but the capability of the Type A media drops rapidly as compared to the Type B media for greater layer thicknesses.

FIG. 11 is a graphical representation of side track erase (STE) loss (dB) for various media types. The STE losses are expressed in terms of bit error rate (BER)
25 loss. The data in FIG. 11 were evaluated for a prewritten track located 10 microinches (10⁻⁶ in) from an adjacent center track after a succession of writes to the center track.

The data in FIG. 11 are from four (4) different test media with different characteristics. A first Type A media (Type A-1) had a KuV/kT value of approximately 105. A second Type A media (Type A-2) had a KuV/kT value of
30 approximately 130. A first Type B media (Type B-1) had a KuV/kT value of

-12 -

approximately 105. A second Type B media (Type B-2) had a KuV/kT value of approximately 130. For reference, Ku represents the uniaxial magnetic anisotropy energy; V is the magnetic layer volume; k is Boltzmann's constant; and T is the measured temperature. The value KuV/kT represents a thermal stability value for the respective media types.

From FIG. 11 it can be observed that using larger thermal stability values for both types of media reduced STE loss; that is, both Type A-2 and Type B-2 media with a KuV/kT of 130 exhibited better performance as compared to the Type A-1 and Type B-1 media with a KuV/kT of 105. For both thermal stability values, the Type A media exhibited lower STE loss as compared to the Type B media. This indicates that STE loss in PMR media can be reduced using larger thermal stability values and stronger magnetic exchange coupling type media.

FIG. 12 is a graphical representation of areal density capability (ADC) data in terms of gigabits per square inch, $Gbits/in^2$ (1×10^{12} bits/ in^2) for the various media types from FIG. 11. The ADC is expressed in terms of Mst, kuV/kT and STE loss after 50,000 center track writes.

As discussed above with respect to FIG. 11, STE loss can be reduced by increasing the thermal stability value KuV/kT in both types of media. FIG. 12 shows that the Type A media exhibits an improvement in STE loss from 1.15 dB to 0.75 dB as KuV/kT is increased from 105 to 130, and the Type B media exhibits similar improvement in STE loss from 1.33 dB to 0.95 dB as KuV/kT is increased from 105 to 130.

However, the reduction of the STE loss in the Type A media also induces a larger ADC loss, from about 525 $Gbits/in^2$ to about 515 $Gbits/in^2$, as compared to the Type B media which only exhibits an ADC loss of from about 527 $Gbits/in^2$ to about 526 $Gbits/in^2$. Accordingly, the enhanced exchange decoupling of the Type B media formulation also has the benefit of promoting higher areal densities for the PMR media.

-13 -

While the foregoing illustrative embodiments have used Rh as the platinum group element added to the CoPt cores in the granular recording media, the other platinum group elements Ru, Rh, Pd, Os and Ir, and alloys thereof, may also be used.

Further embodiments of the present disclosure are directed a CoPtCrRh alloy recording layer. As before, Rh is added to reduce the total amount of Co content and reduce exchange coupling and stiffness while maintaining moment and anisotropy. Other elements may be added, such as but not limited to Ir, Fe and/or Ni. In further embodiments, a CoPtCrBRh alloy is provided. As before, the addition of Rh lowers exchange coupling and increases Hk.

In a first example formulation of these additional embodiments, a recording layer is formed of Co₆₀Pt₂₂Cr₈Rh₁₀ (60% Co, 22% Pt, 8% Cr, 10% Rh). The inventors have found that a layer formed of Co₆₀Pt₂₂Cr₈Rh₁₀ has nominally the same Ms and a higher Hk than a baseline layer of Co₆₈Pt₂₂Cr₁₀, but with a reduction of Co concentration of 8% as compared to the baseline layer. Thus, lower anisotropy magnetic elements having much lower quantum mechanical exchange stiffness Fe (or Ni) can replace Co to reach the same Hk value, and a further small adjustment to the Cr concentration can maintain the same Ms.

In a second example formulation, replacing 6%Co with 5%Fe plus 1%Cr in the Co₆₀Pt₂₂Cr₈Rh₁₀ material provides Co₅₄Pt₂₂Cr₉Rh₁₀Fe₅ for the recording layer, which has similar Ms and Hk values as the Co₆₀Pt₂₂Cr₈Rh₁₀ material but with 14% less Co as compared to the baseline Co₆₈Pt₂₂Cr₁₀ material. This second formulation provides a correspondingly lower exchange stiffness, lower exchange coupling and lower tendency toward undesirable domain wall rotation or in-plane magnetization.

In a third example formulation, 6% of the Co in the (first) Co₆₀Pt₂₂Cr₈Rh₁₀ material is replaced with lower Ms element Ni at 8%, and 2% of the Cr is removed to provide an alloy of Co₅₄Pt₂₂Cr₆Rh₁₀Ni₈ for the recording layer. This provides another alloy with the same nominal amounts of moment and anisotropy, but with lower exchange stiffness.

While nickel has been used as a component in longitudinal recording layer alloys in the 1980's, such alloys had much lower anisotropy Ku and coercivity

-14 -

($H_c < 4,000$ Oe) than current generation materials. Owing to the need for high anisotropy materials and coercivity levels of $H_c > 5,000$ Oe, conventional perpendicular recording has taught away from these materials. Products by all media manufacturers have used Co as the magnetic element for the hard recording layer, in combination with polarizable Pt that also increases anisotropy and exchange stiffness. The art has generally instructed only Co-Pt alloys for both the oxide “granular” and Cr+B containing “CGC” metallic layers of the conventional perpendicular recording structure. Proposed advanced structures such as multilayers and ordered alloys are separate from the scope of this discussion as those materials obtain their anisotropy from the relative position of this discussion as those materials obtain their anisotropy from the relative position of different elements within the structure, not the anisotropy of the elements themselves.

Conventional sputtered CoCrPt alloys tend to have a maximum K_u of around 7×10^6 for 70% Co. It has been found that alloys in formulations with 65%, 60%, 55% or other values of Co can achieve levels of K_u of 7×10^6 or more using the same sputter process. These embodiments are exemplary only. A large range of compositions of alloy recording layers having CoPt can have anisotropy maintained with exchange stiffness lowered by the addition of materials including Ni, Fe and Rh in accordance with the foregoing discussion. It may be used as a substitute for the Rh in some cases. These materials containing at least one of the specified elements can be applied to oxide containing granular magnetic layers of a magnetic recording layer, as well as the substantially oxide free metallic or CGC layers.

The foregoing embodiments including Rh or Ir along with Co and $15\% \leq \text{Pt} \leq 30\%$ tend to maximize the increase in anisotropy of the Co-Pt alloy, increasing the amount of Co that can be removed, and/or the amount of Fe or Ni that can be added without losing anisotropy compared to conventional Co-Pt alloys that do not include such elements.

A fourth example formulation adds Rh to a CoCrPtB alloy to provide a CoCrPtBRh alloy for one or more of the recording layers in FIGS. 1-2. For example, a conventional CoCrPtB formulation may take the form $\text{Co}_{64}\text{Cr}_{15}\text{Pt}_{12}\text{B}_9$. The B is

-15 -

provided in an effort to lower exchange coupling in a continuous magnetic recording layer. However, using B in an exchange layer can provide a severe penalty. Due to its small atomic radius, B atoms tend to stay between crystalline lattice dots.

When CoCrPtB is deposited onto a media stack, the B will tend to scramble the HCP lattice causing defects such as stacking faults, which reduce magnetic anisotropy. A conventional approach to addressing this is to increase the percentage of Pt. However, the inventors have found that CoCrPtB films tend to consistently exhibit low Hk no matter how much Pt is added to compensate.

Accordingly, the fourth example formulation decreases at least the amount of Co and/or B and adds Rh to provide a CoCrPtBRh alloy. In some embodiments, the alloy is Co₆₄Cr₁₅Pt₁₂B₂Rh₇, with 7% Rh being added to replace a corresponding 7% of the B content. Other formulations are contemplated, including formulations that reduce the Co content by a corresponding amount of Rh, such as Co₆₀Cr₁₅Pt₁₂B₂Rh₁₁. These and other formulations have been found to increase Hk while maintaining moment, reducing exchange coupling and stiffness and reducing stacking faults and other defects.

To demonstrate the efficacy of adding Rh to a CoCrPtB or CoCrPtB-oxide alloy, FIG. 13 graphically represents anisotropy (Hk) test data from various CoCrPtB and CoCrPtB-oxide alloys with different percentage weight at.% of Pt. It can be seen that increasing Pt by itself fails to significantly increase Hk. FIG. 14 graphically represents anisotropy (Hk) test data for these same formulations, demonstrating that Hk is influenced primarily by the percentage of B.

FIG. 15 is a graphical representation of HCP fraction, or portion of the film layer without stacking fault defects, in relation to the percentage of B. Generally, increasing B content will tend to induce more stacking faults and lower HCP fraction.

FIG. 16 provides additional graphical data for Hk with respect to percentage Pt. Generally, the data are scattered as represented previously in FIG. 13. The data points are separated into those with relatively lower B content, represented by the circles for formulations with B at.% of about 0-2%, and those with relatively higher B content, represented by the circles for formulations with B at.% of about 3-12%. It

-16 -

can be seen that in the low B alloys, Hk is still strongly dependent on Pt%. For the higher B alloys, Hk is less dependent upon Pt%. Accordingly, it can be concluded that simply adding more Pt will not be effectual in raising Hk.

FIG. 17 provides a graphical representation of HCP fraction for the formulations of FIG. 16. This confirms that higher B% tends to increase the occurrence of stacking faults (e.g., lower HCP fraction).

Accordingly, adding Rh in substitution for a portion of the Co and/or B can provide improved exchange decoupling, higher Hk and reduced stacking faults. Some test results indicate improvements in Hc with the addition of Rh by about 300 Oe or more, and enhanced kBPI and kTPI levels.

FIG. 18 is a graphical representation of change (Δ) in track pitch levels for a CGC structure having at least one layer with a conventional CoCrPtB alloy (represented by the circles and “no Rh” label) and a CGC structure having at least one layer with a CoCrPtBRh alloy (represented by the diamonds and the “w/ Rh” label). Side track erase (STE) loss increases at a higher rate for the softer conventional formulation as compared to the disclosed formulation of the present embodiment. Thus, Rh can be added to a CoCrPtB alloy to (including a CoCrPtB-oxide alloy) to retain the benefits of the addition of B while still obtaining higher Hk and lower exchange coupling.

Without limitation, the various embodiments disclosed herein can be characterized in accordance with the following features, alone or in combination as a perpendicular magnetic recording medium comprising a recording layer formed of: Co, Pt and a platinum group metal; specifically a CoPtRh alloy; a CoPtCrRh alloy; a CoPtCrBRh alloy; the alloy has a Co percentage of nominally 65% or less; a Co percentage of 60% or less; a Co percentage of nominally 55% or less; the alloy has a Pt percentage of between nominally 15% and 30%; the alloy is Co₆₀Pt₂₂Cr₈Rh₁₀, Co₅₄Pt₂₂Cr₉Rh₁₀Fe₅, Co₅₄Pt₂₂Cr₆Rh₁₀Ni₈, Co₆₄Cr₁₅Pt₁₂B₂Rh₇, or Co₆₀Cr₁₅Pt₁₂B₂Rh₁₁; the recording layer is supported by a substrate and comprises Co, Pt, Cr and Rh; the data recording layer further comprises B; the data recording layer further comprises Fe and Ni; the Co percentage is nominally 65% or less; the Co

-17 -

percentage is nominally 60% or less; the Co percentage is nominally 55% or less; the data recording layer has a Pt percentage of between nominally 15% and 30%; and the recording layer is a granular lower layer in a CGC structure. Other combinations are contemplated in view of the present disclosure.

5 It is to be understood that even though numerous characteristics and configurations of various embodiments of the present disclosure have been set forth in the foregoing description, together with details of the structure and function of various embodiments, this detailed description is illustrative only, and changes may be made in detail, especially in matters of structure and arrangements of parts within the
10 principles of the technology to the full extent indicated by the broad general meaning of the terms in which the appended claims are expressed. For example, the particular elements may vary depending on the particular application without departing from the spirit and scope of the present disclosure.

-18 -

Claims:

1. A perpendicular magnetic recording medium comprising a granular magnetic recording layer comprising an alloy of cobalt (Co), platinum (Pt) and a platinum group metal element to decrease intra-layer exchange coupling between adjacent grains.

2. The medium of claim 1, wherein the platinum group metal element is rhodium (Rh).

3. The medium of claim 1, further comprising a continuous magnetic recording layer supported by the granular magnetic recording layer to form a continuous granular composite (CGC) structure.

4. The medium of claim 1, wherein the granular magnetic recording layer further comprises chromium (Cr) to provide magnetic grains of CoCrPtRh alloy.

5. The medium of claim 4, wherein the granular magnetic recording layer further comprises boron (B) to provide magnetic grains of CoCrPtBRh alloy.

6. The medium of claim 4, wherein the granular magnetic recording layer further comprises iron (Fe) to provide magnetic grains of CoCrPtRhFe.

7. The medium of claim 4, wherein the granular magnetic recording layer further comprises nickel (Ni) to provide magnetic grains of CoCrPtRhNi.

8. The medium of claim 1, wherein the granular magnetic recording layer comprises individual magnetic grains of CoPtRh alloy surrounded by a non-magnetic oxide material.

-19 -

5 9. The medium of claim 1, further comprising an exchange breaking layer contactingly supported by the granular magnetic recording layer and a continuous magnetic recording layer contactingly supported by the exchange breaking layer to form a continuous granular composite (CGC) structure of a perpendicular magnetic recording (PMR) medium.

10 10. The medium of claim 1, wherein the platinum group metal element is at least a selected one of ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os) or iridium (Ir).

15 11. A perpendicular magnetic recording medium comprising a granular magnetic recording layer with magnetic grains surrounded by a non-magnetic material, the magnetic recording layer formed of a CoPtRh alloy, the Rh decreasing intra-layer exchange coupling between adjacent grains.

 12. The medium of claim 11, wherein the alloy is CoCrPtRh.

 13. The medium of claim 11, wherein the alloy is CoCrPtBRh.

20 14. The medium of claim 11, wherein the alloy has a Co percentage of nominally 60% or less.

 15. The medium of claim 11, wherein the alloy has a Pt percentage of between nominally 15% and 30%.

25 16. The medium of claim 11, wherein the alloy is Co₆₀Pt₂₂Cr₈Rh₁₀.

 17. The medium of claim 11, wherein the alloy is Co₅₄Pt₂₂Cr₉Rh₁₀Fe₅.

30 18. The medium of claim 11, wherein the alloy is Co₅₄Pt₂₂Cr₆Rh₁₀Ni₈.

-20 -

19. The medium of claim 11, wherein the alloy is $\text{Co}_{64}\text{Cr}_{15}\text{Pt}_{12}\text{B}_2\text{Rh}_7$.
20. The medium of claim 11, wherein the alloy is $\text{Co}_{60}\text{Cr}_{15}\text{Pt}_{12}\text{B}_2\text{Rh}_{11}$.

1/12

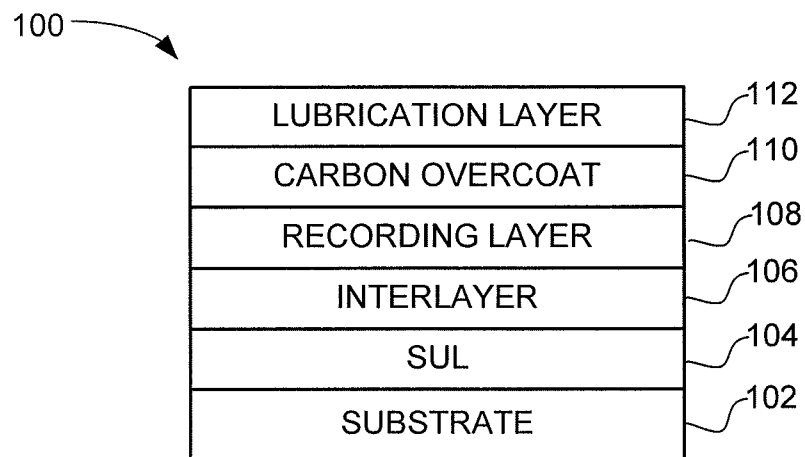


FIG. 1

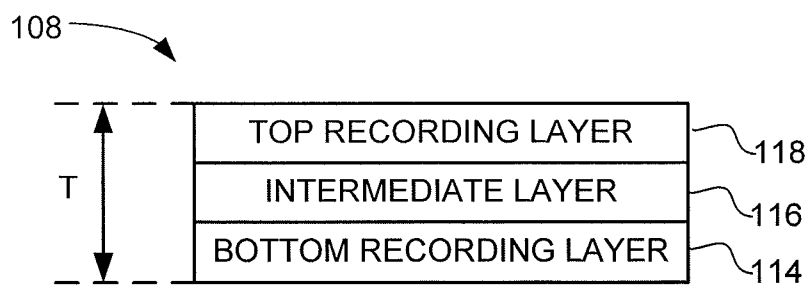


FIG. 2

2/12

MAGNETIC COERCIVITY
(H_c)

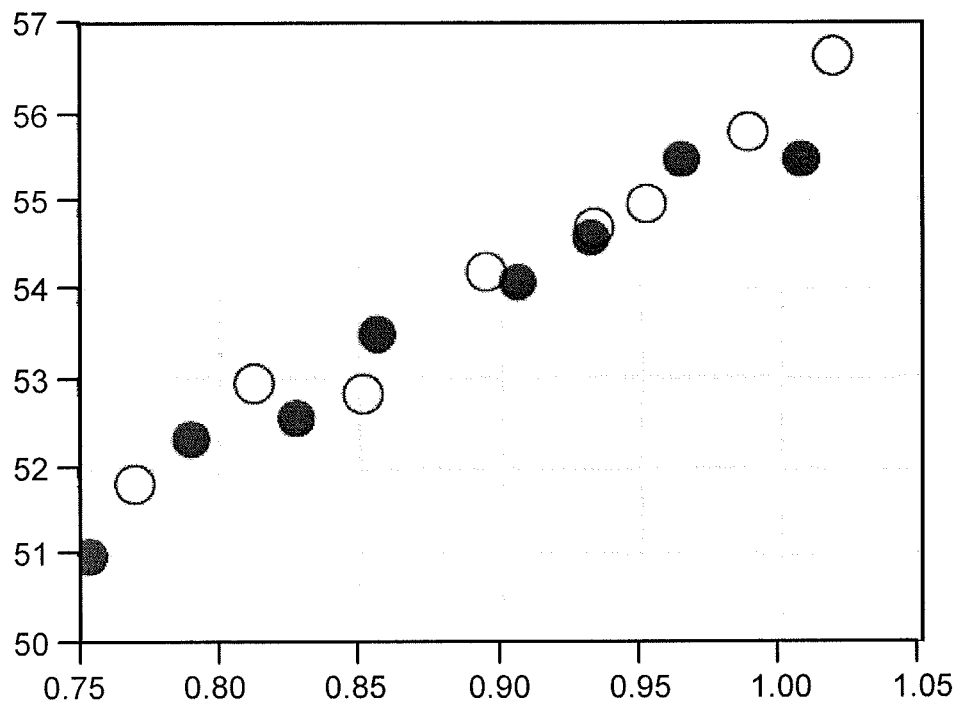


FIG. 3A

MAGNETIZATION FIELD
(H_n)

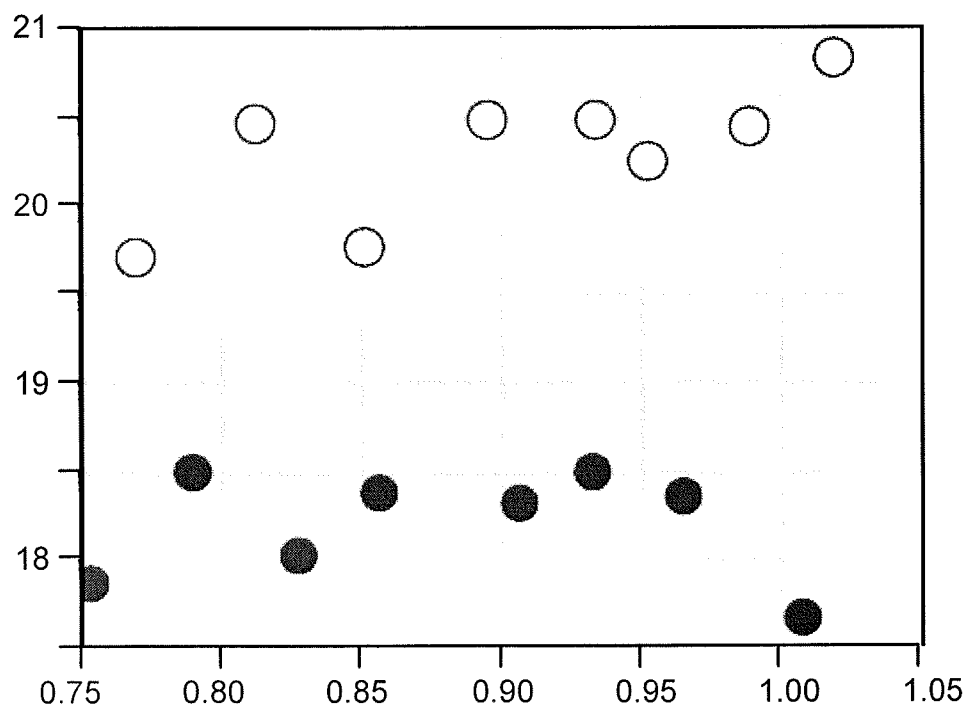


FIG. 3B

3/12

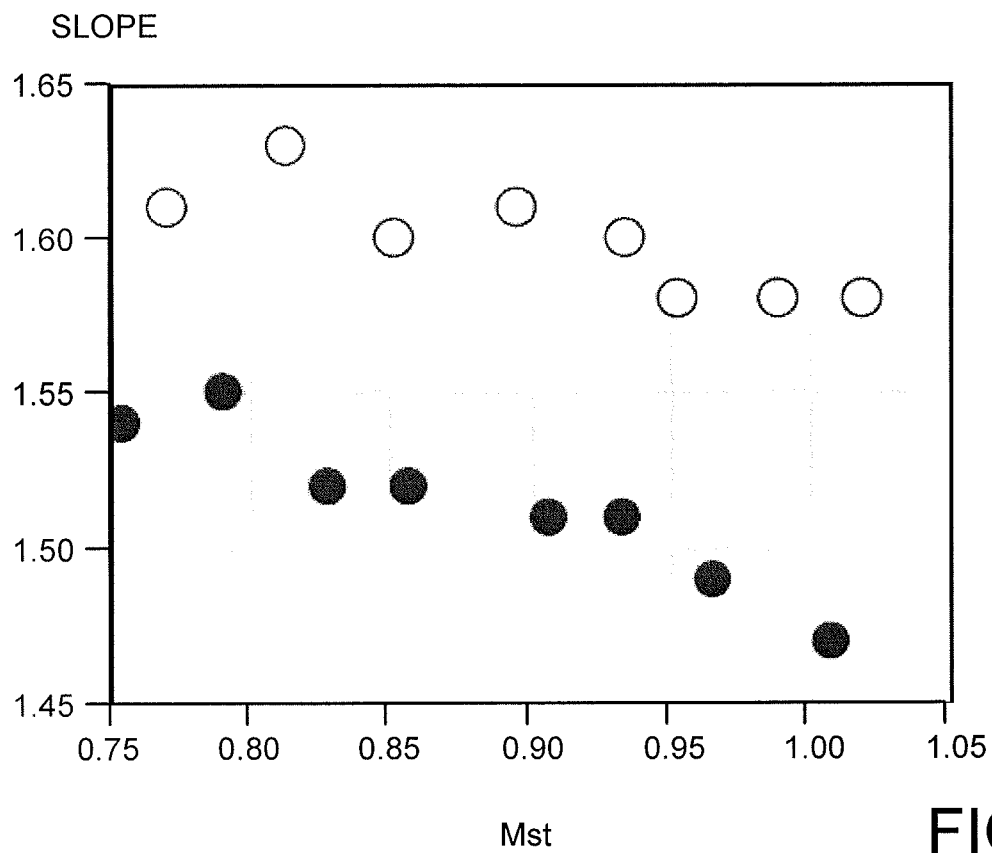


FIG. 4

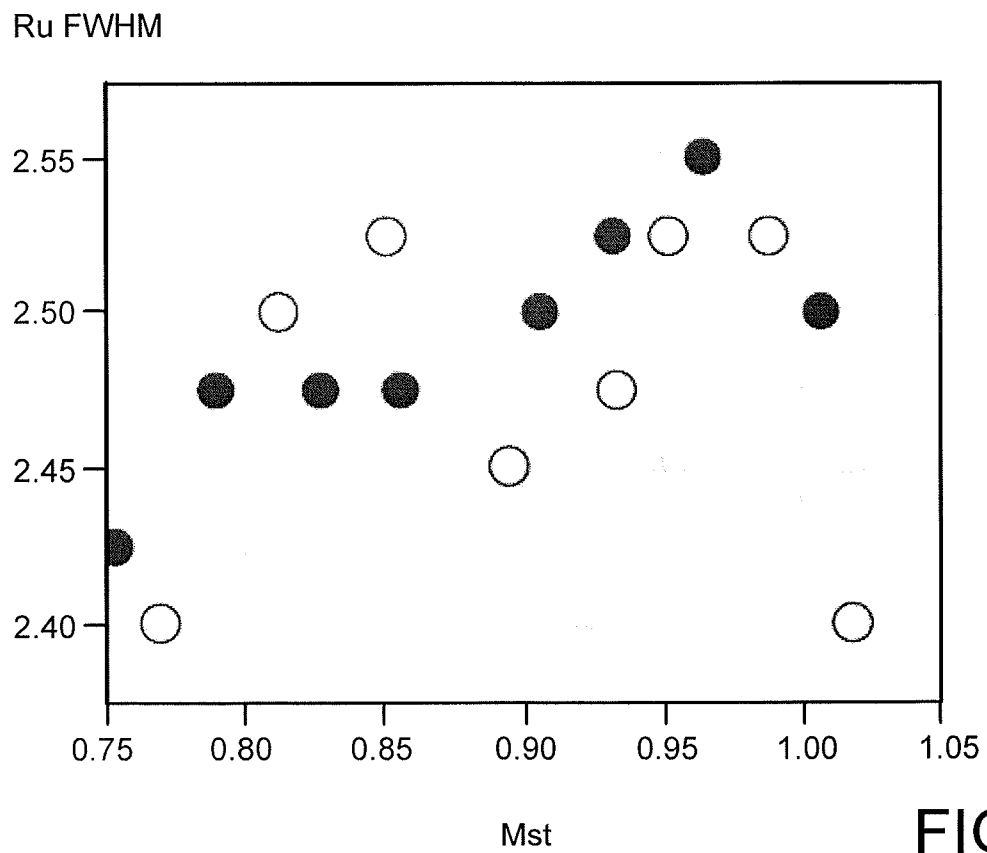


FIG. 5A

4/12

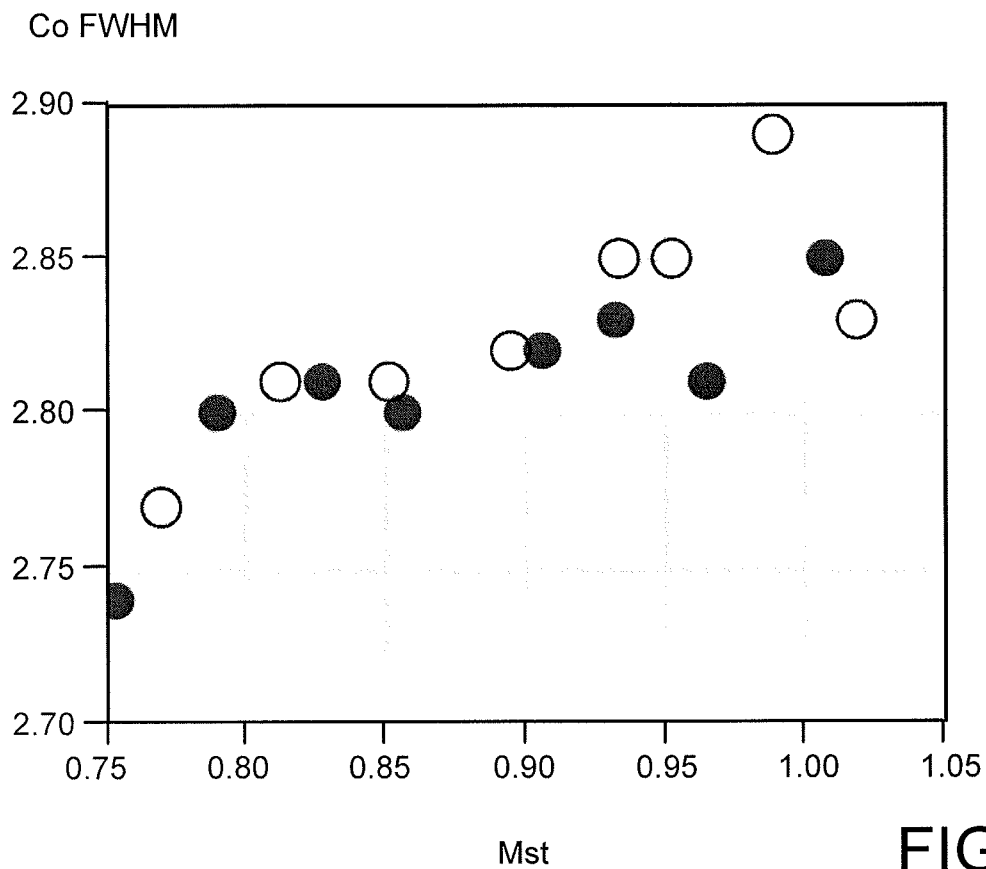


FIG. 5B

DELTA FWHM

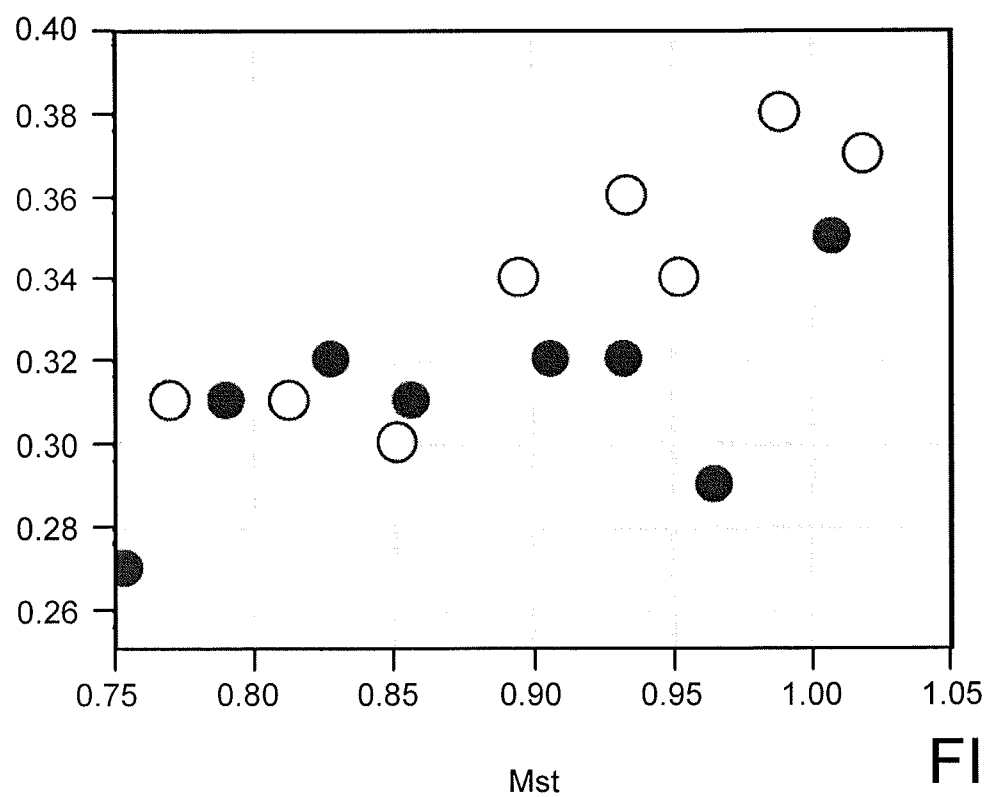


FIG. 6

5/12

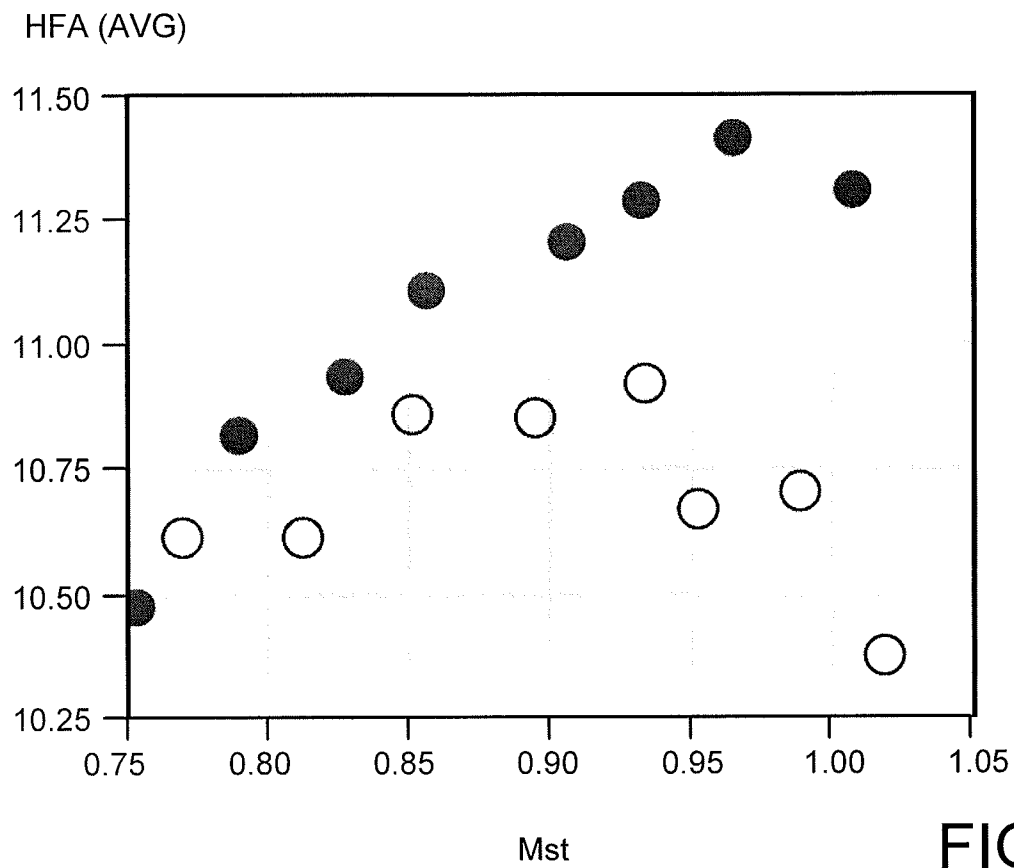


FIG. 7

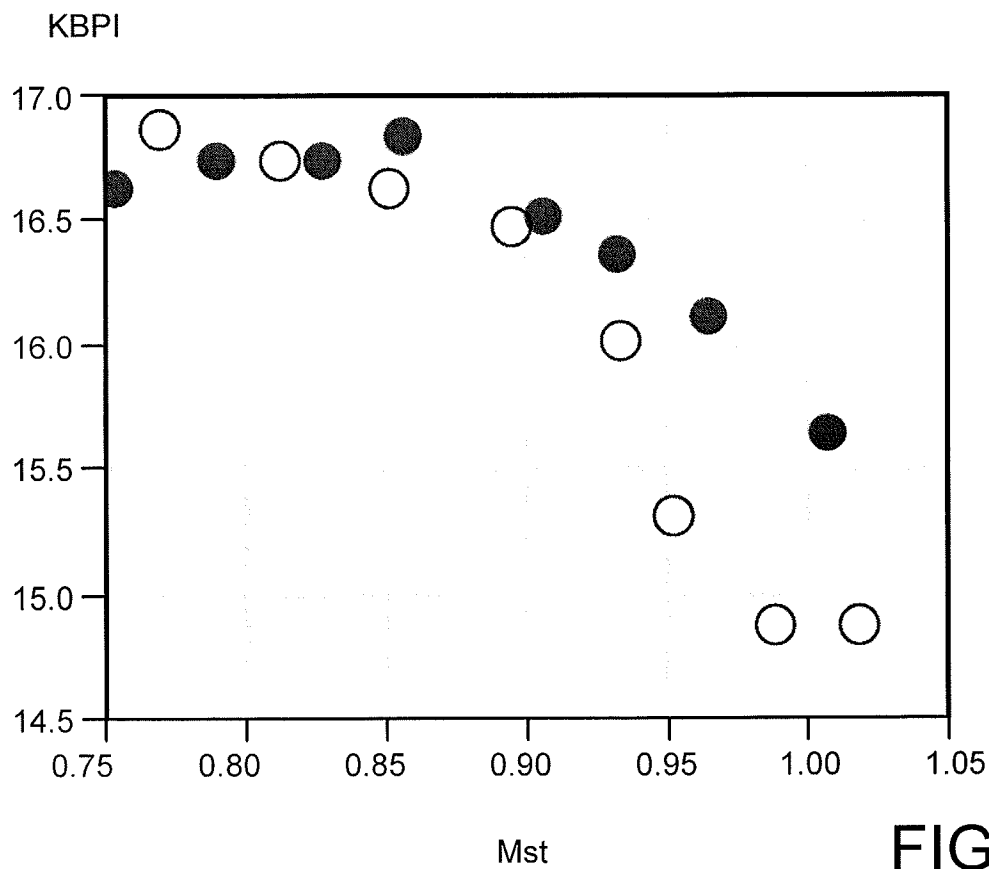


FIG. 8A

6/12

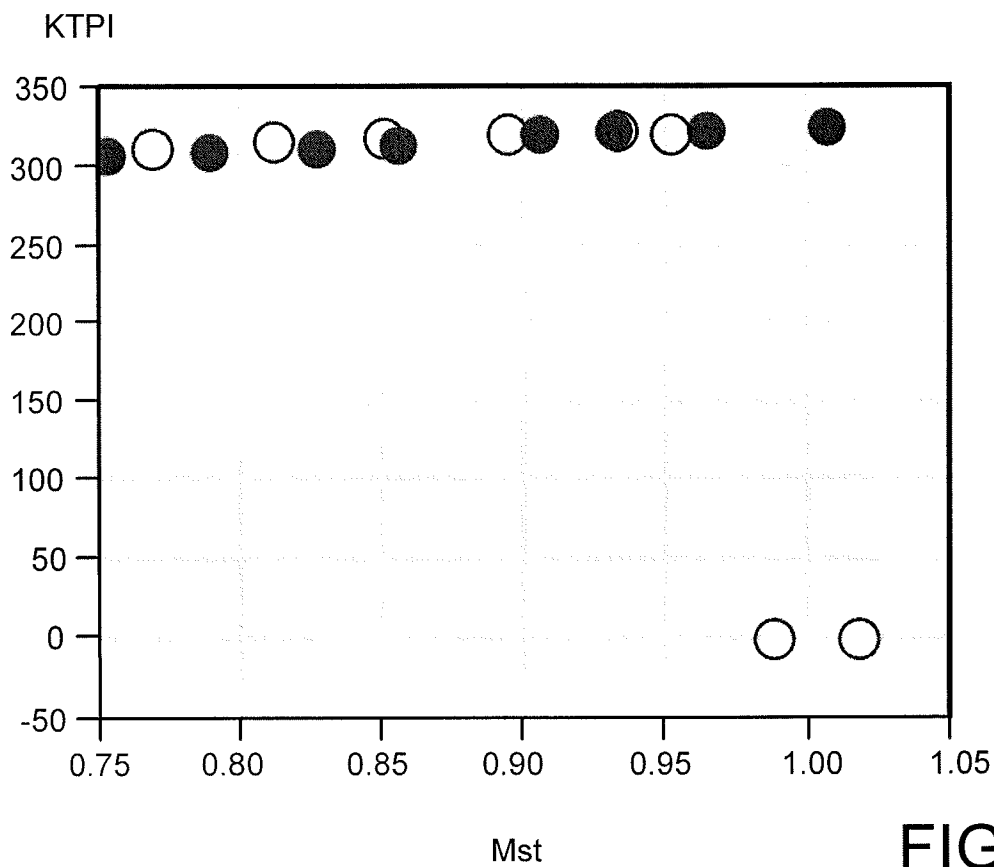


FIG. 8B

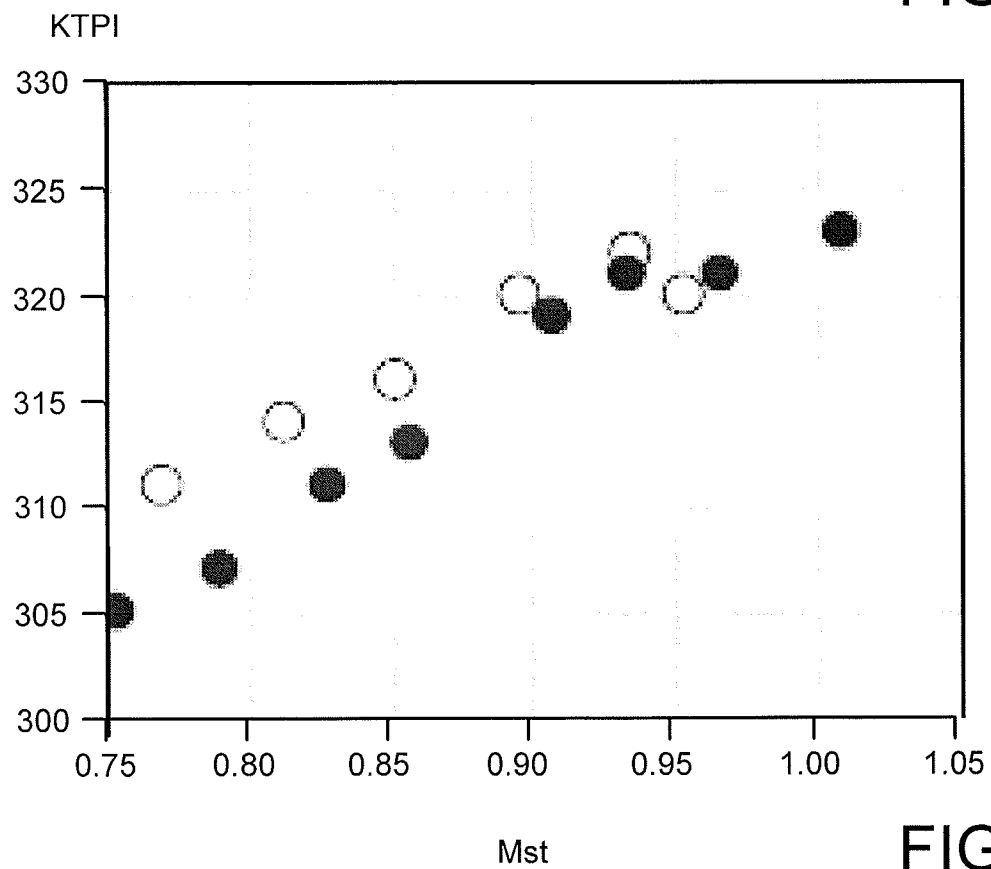
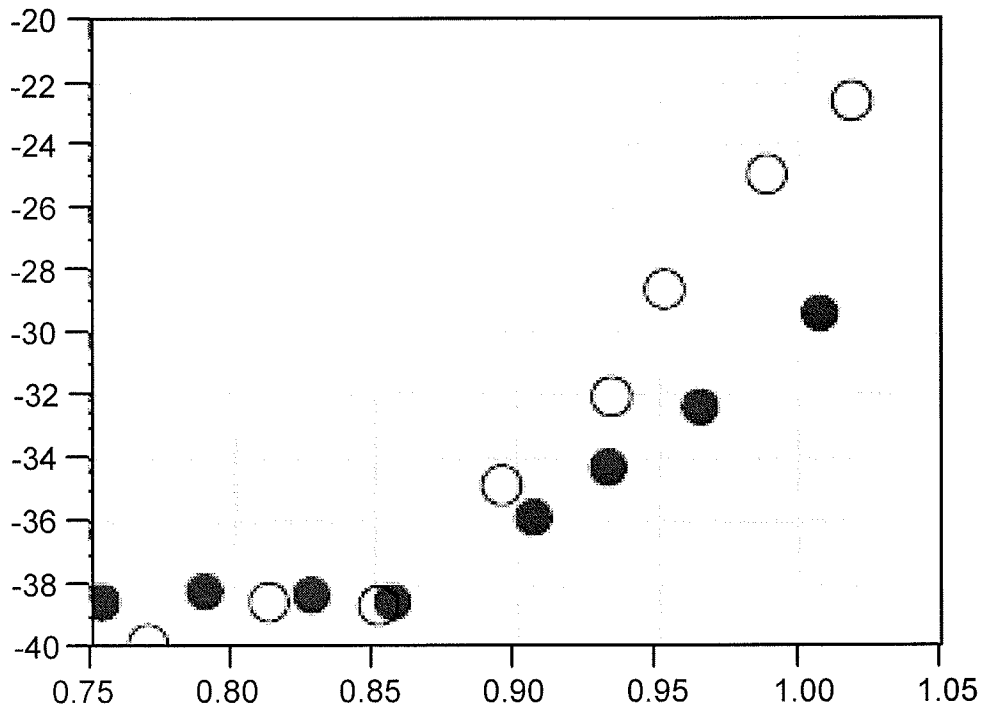


FIG. 8C

7/12

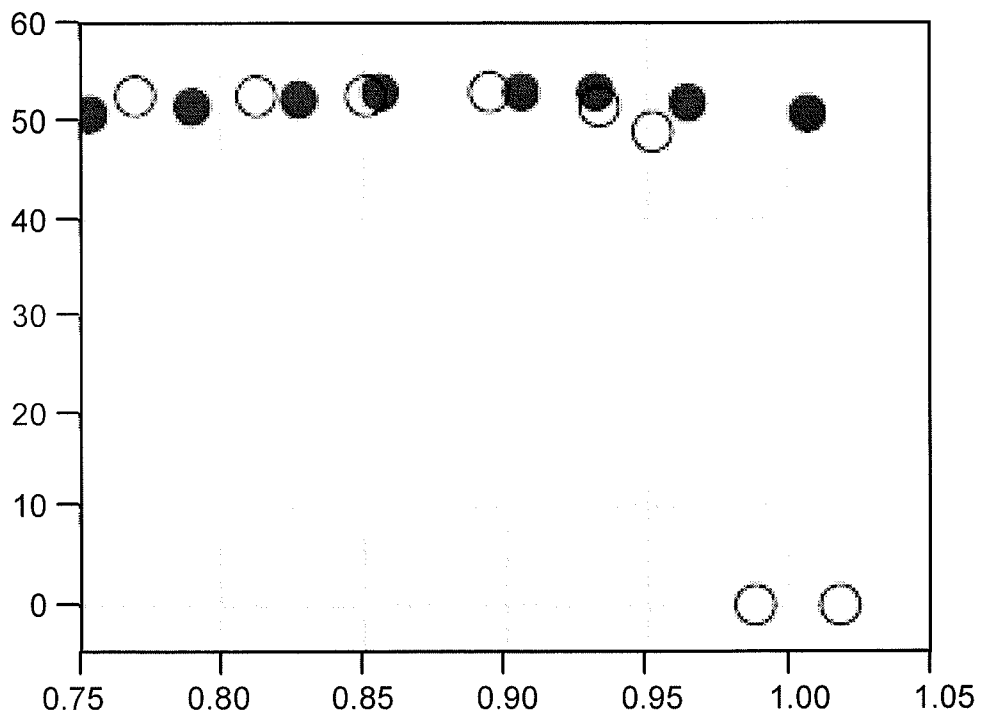
REVERSE OVERWRITE
(dB)



AREAL DENSITY
CAPABILITY

Mst

FIG. 9



Mst

FIG. 10A

8/12

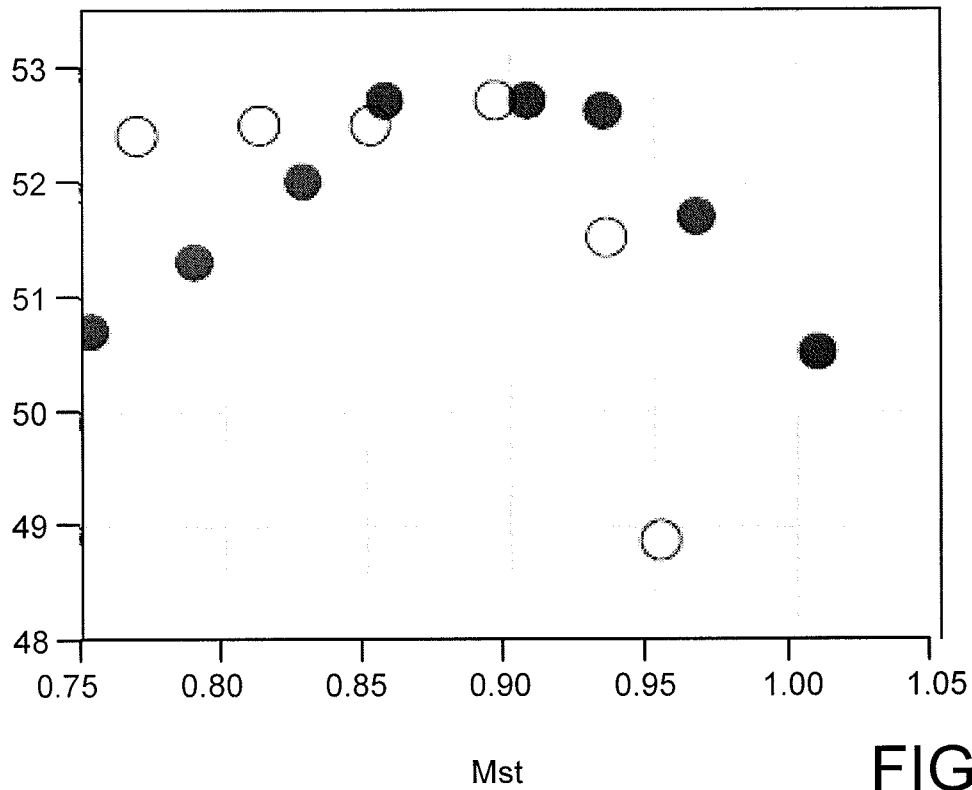
AREAL DENSITY
CAPABILITY

FIG. 10B

BIT ERROR RATE LOSS

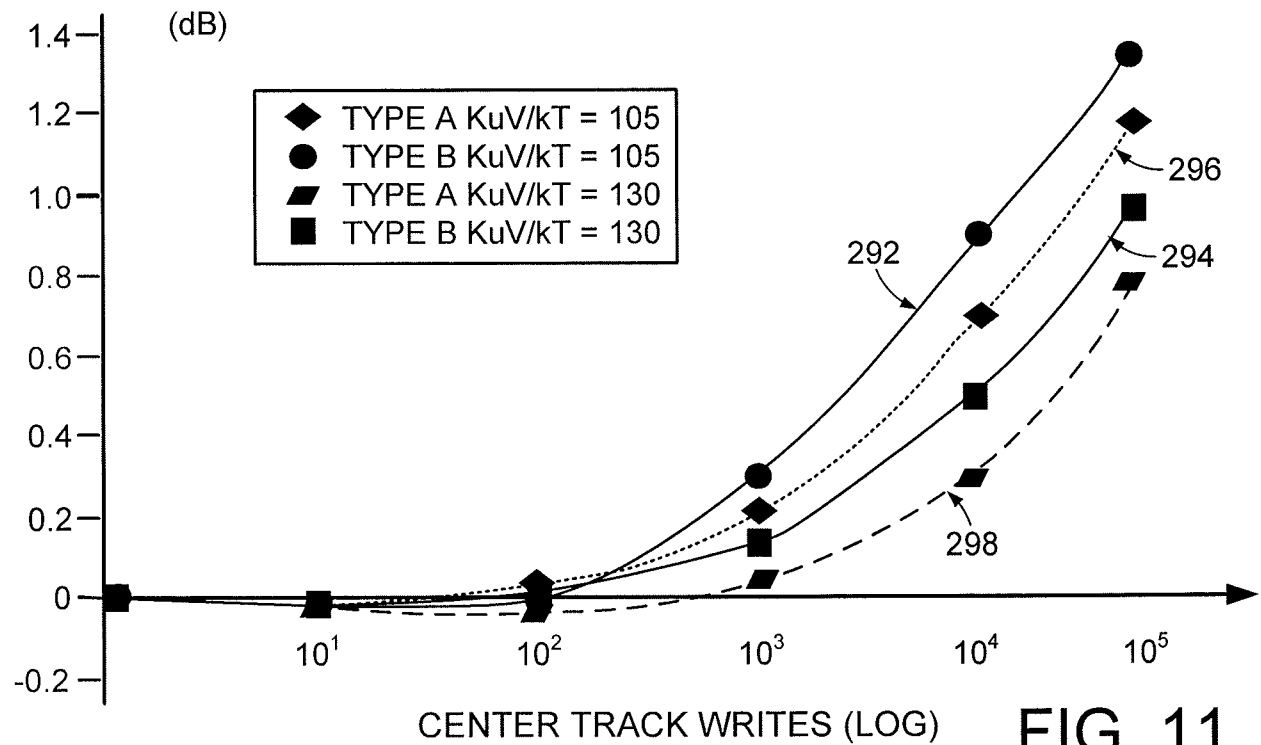


FIG. 11

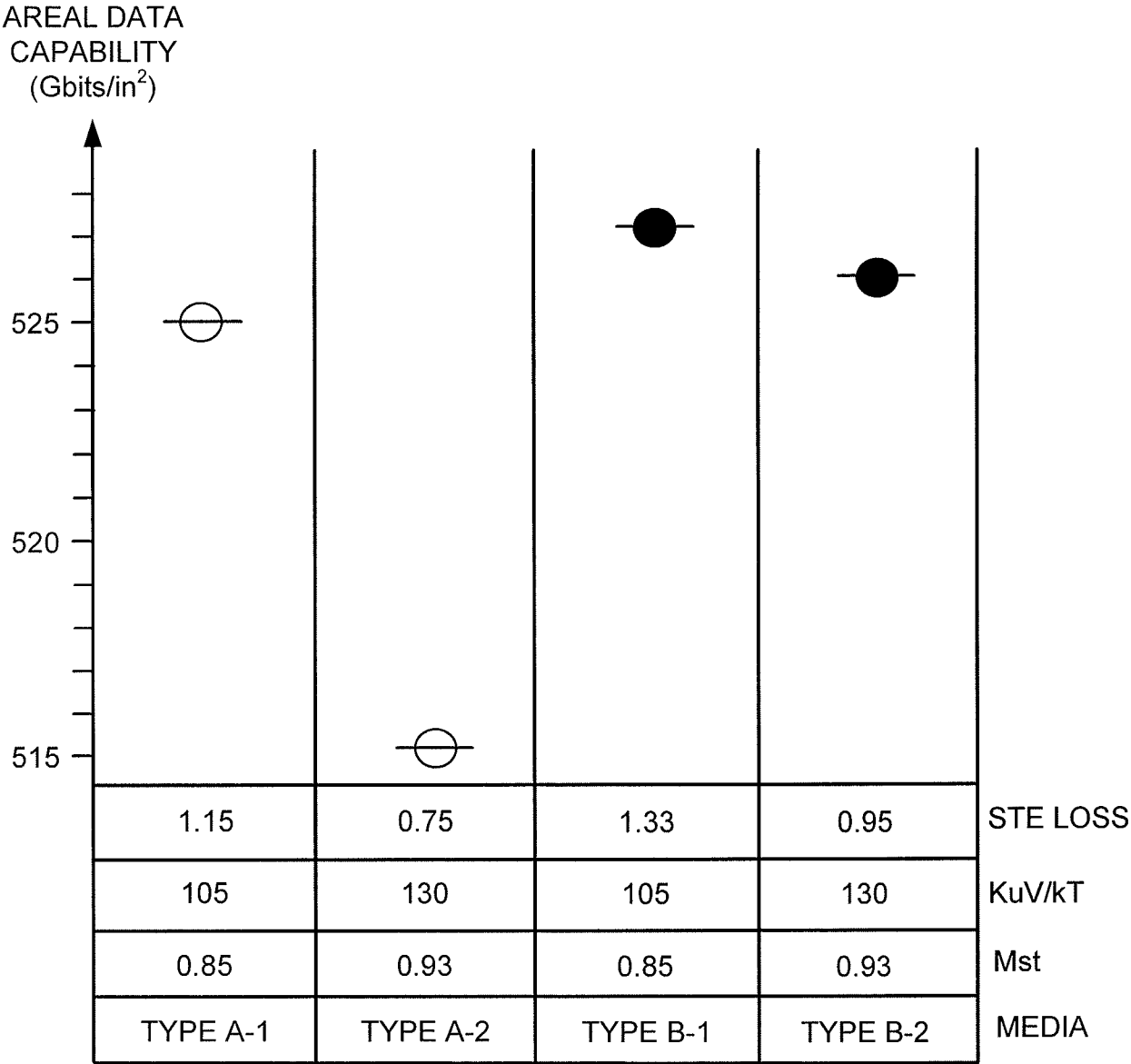


FIG. 12

10/12

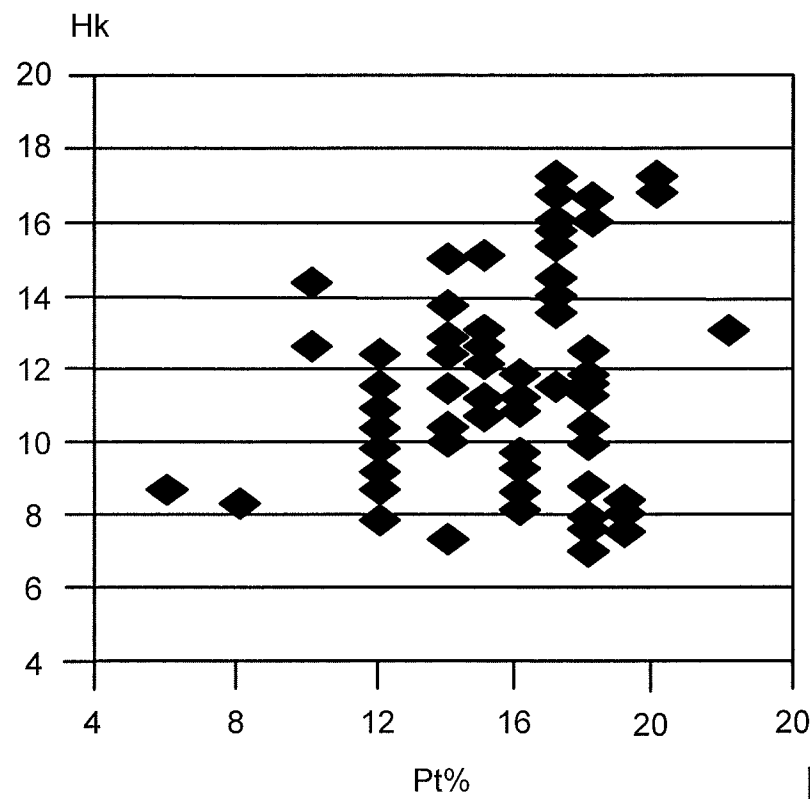


FIG. 13

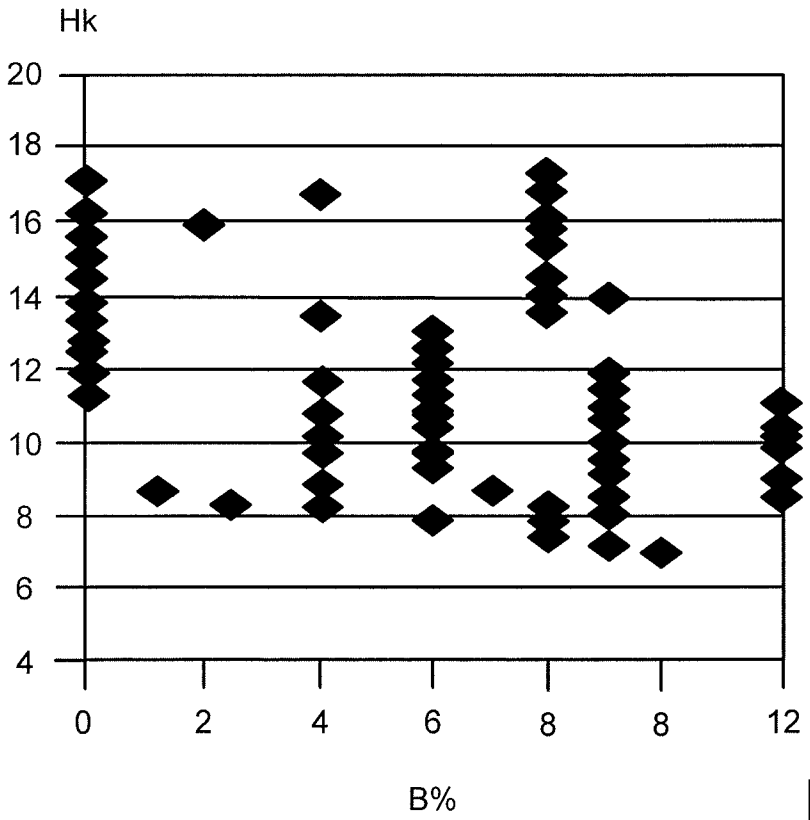


FIG. 14

11/12

HCP FRACTION

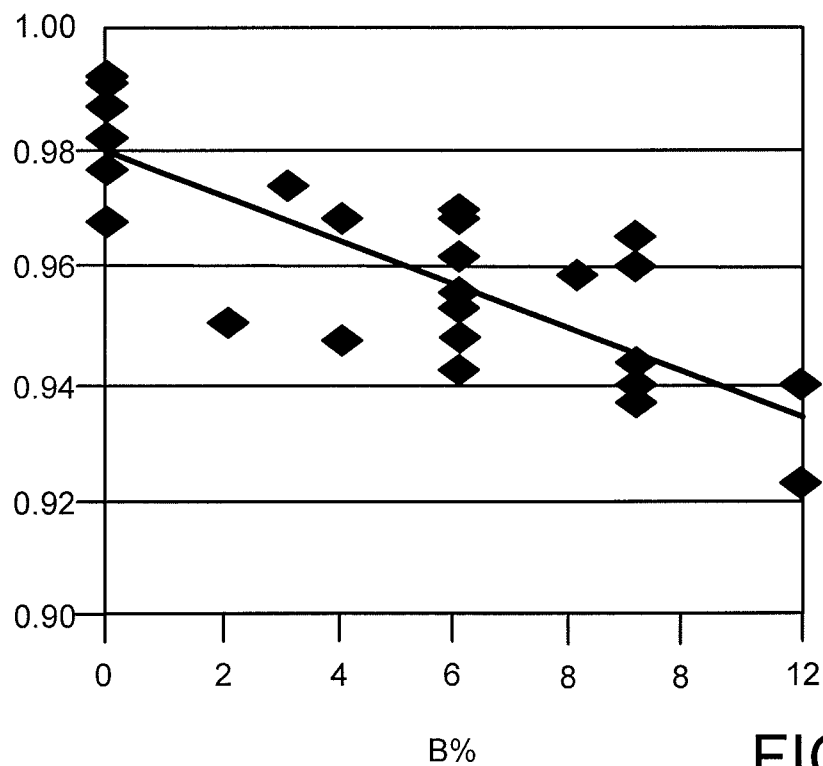


FIG. 15

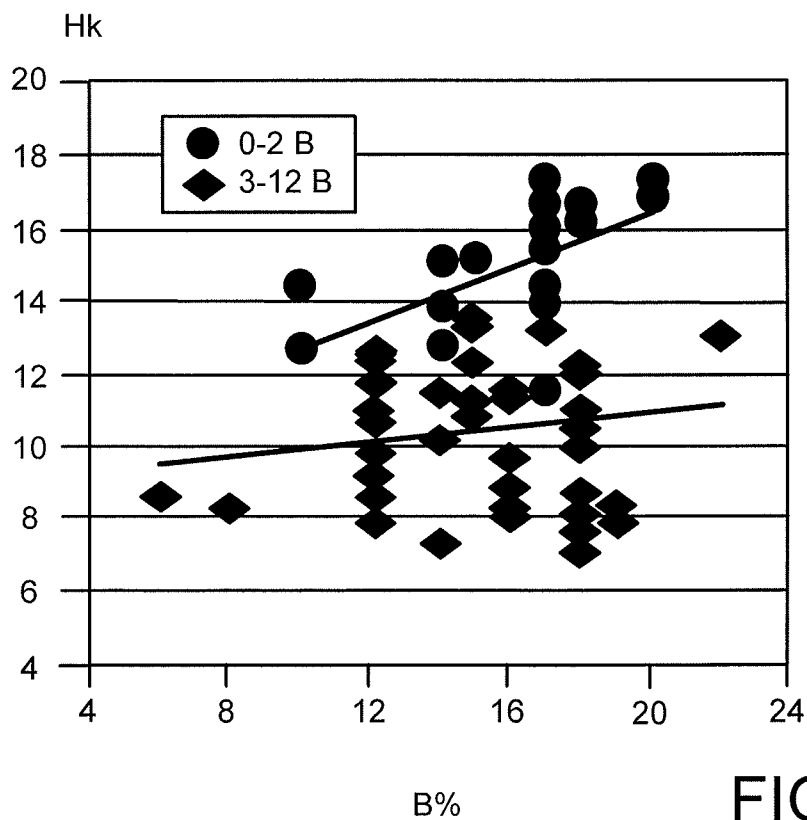


FIG. 16

12/12

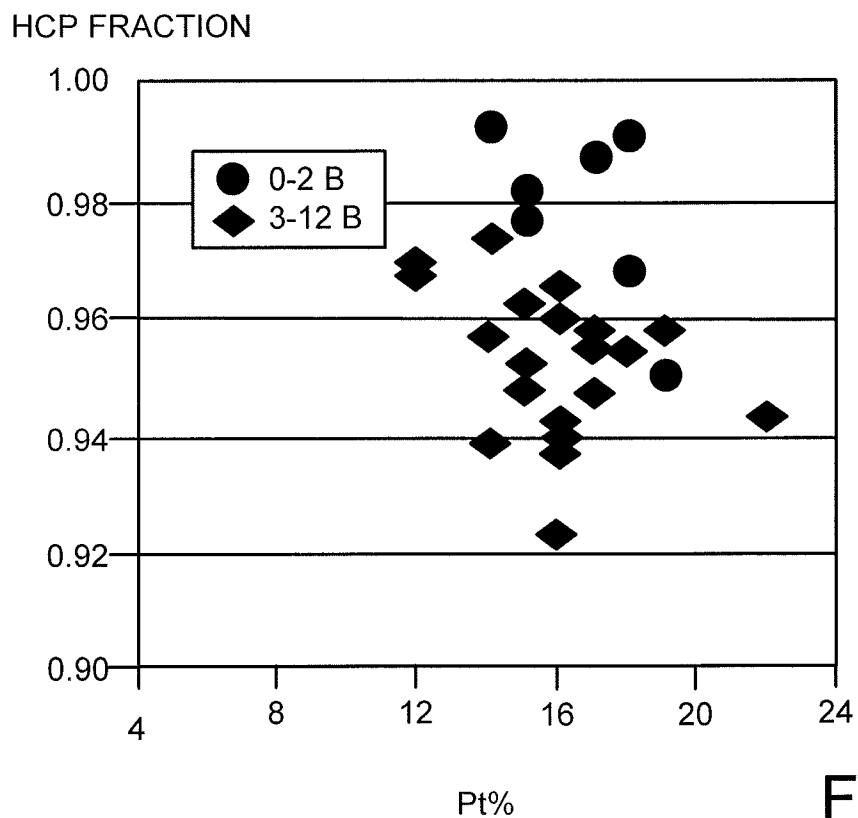


FIG. 17

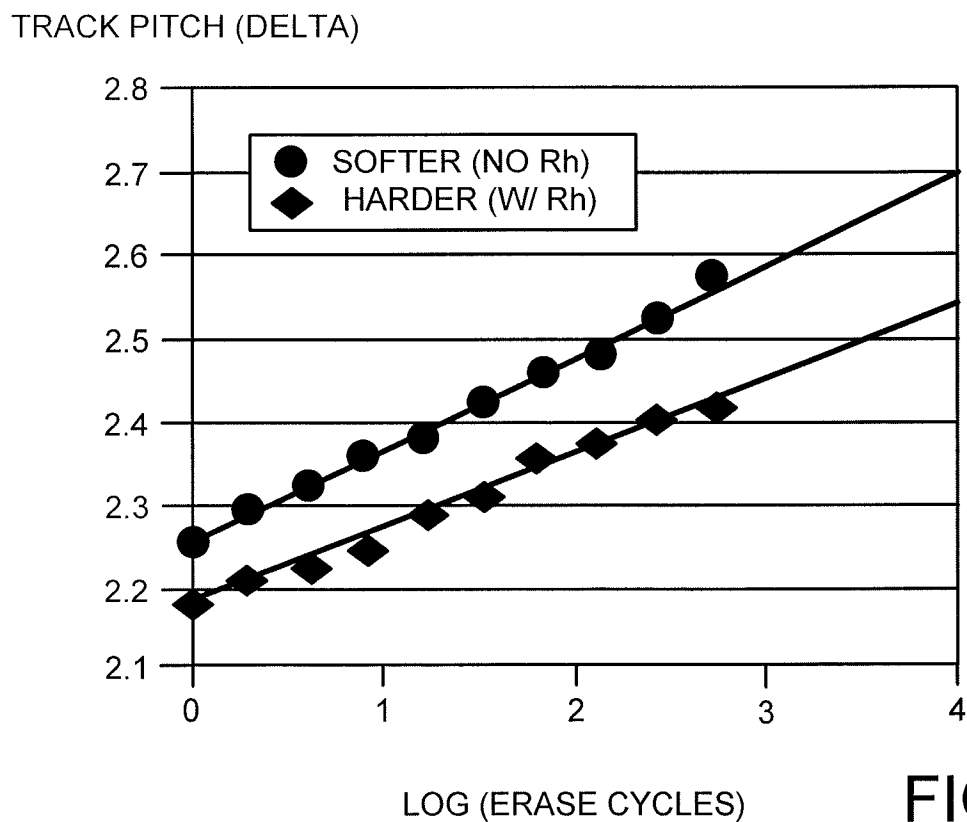


FIG. 18

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2014/071625**A. CLASSIFICATION OF SUBJECT MATTER****G11B 5/66(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)

G11B 5/66; G11B 5/33; G11B 5/17; G11B 5/62; C23C 14/35; C23C 14/34; G11B 5/127; G11B 5/64

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: perpendicular magnetic recording medium, cobalt, platinum, rhodium, exchange coupling, reduce, and similar terms.**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2010-0247962 A1 (YUZO SASAKI) 30 September 2010 See paragraph [0011].	1-20
Y	US 2009-0092858 A1 (SHENG-CHI CHEN et al.) 09 April 2009 See paragraphs [0054]-[0056].	1-20
Y	US 2005-0058855 A1 (EROL GIRT) 17 March 2005 See paragraphs [0017]-[0046].	4-8, 10, 12-20
A	KR 10-2008-0052134 A (HERAEUS INC.) 11 June 2008 See paragraphs [0020]-[0027].	1-20
A	US 2005-0068688 A1 (RACHID SBIAA et al.) 31 March 2005 See paragraphs [0022]-[0024], [0081]-[0090]; and claims 8, 12.	1-20



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

26 March 2015 (26.03.2015)

Date of mailing of the international search report

27 March 2015 (27.03.2015)

Name and mailing address of the ISA/KR

International Application Division
Korean Intellectual Property Office
189 Cheongsu-ro, Seo-gu, Daejeon Metropolitan City, 302-701,
Republic of Korea

Facsimile No. ++82 42 472 7140

Authorized officer

BYUN, Sung Cheal

Telephone No. +82-42-481-8262



INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2014/071625

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2010-0247962 A1	30/09/2010	CN 101816042 A JP 2009-087500 A US 8247094 B2 WO 2009-044794 A1	25/08/2010 23/04/2009 21/08/2012 09/04/2009
US 2009-0092858 A1	09/04/2009	TW 200917240 A	16/04/2009
US 2005-0058855 A1	17/03/2005	US 7842409 B2	30/11/2010
KR 10-2008-0052134 A	11/06/2008	CN 101276599 A CZ 20070154 A3 EP 1930884 A1 JP 2008-146801 A SG 143108 A1 TW 200825190 A US 2008-0131735 A1	01/10/2008 23/07/2008 11/06/2008 26/06/2008 27/06/2008 16/06/2008 05/06/2008
US 2005-0068688 A1	31/03/2005	JP 2005-109241 A US 7522389 B2	21/04/2005 21/04/2009