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Middle Shields Two-Dimensional Magnetic Recording Read Heads

Abstract

The present disclosure generally relates to a dual free layer two dimensional magnetic recording read head. The read head comprises a first lower shield, a first sensor disposed over the first lower shield, a first upper shield disposed over the first sensor, a read separation gap (RSG) disposed on the first upper shield, a second lower shield disposed over the RSG, a second sensor disposed over the second lower shield, and a second upper shield disposed over the second sensor. In some embodiments, the second lower shield comprises a CoFeHf layer. In another embodiment, the second lower shield is a synthetic antiferromagnetic multilayer comprising a first shield layer, a second shield layer, and a CoFe/Ru/CoFe anti-ferromagnetic coupling layer or a Ru layer disposed therebetween, the first and second shield layers comprising NiFe and CoFe. In yet another embodiment, the second lower shield comprises layers of Ru, IrMn, and NiFe.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application is a divisional of co-pending U.S. patent application Ser. No. 18/226,615, filed July 26, 2023, which claims benefit of U.S. provisional patent application Ser. No. 63/421,488, filed Nov. 1, 2022, both of which are herein incorporated by reference.

BACKGROUND OF THE DISCLOSURE
Field of the Disclosure
[0002] Embodiments of the present disclosure generally relate to a dual free layer (DFL) two dimensional magnetic recording (TDMR) read head.
Description of the Related Art
[0003] Two dimensional magnetic recording (TDMR) read heads generally have a first sensor, oftentimes referred to as a lower reader and a second sensor, oftentimes referred to as an upper reader. The readers each have lower and upper shields with an insulating reader separation gap (RSG) therebetween. Both the top reader and the bottom reader are substantially identical, each comprising two free layers to be dual free layer (DFL) readers or sensors. In DFL reader operation, the two free layers or each reader are individually stabilized longitudinally by an anti-ferromagnetically coupled (AFC) soft bias (SB) and biased transversally by a permanent magnet or a rear hard bias (RHB) structure from the stripe back edge of the sensor.
[0004] A transverse bias field of TDMR read heads is determined by the remnant magnetization (Mr) times thickness (t) product (i.e., Mr*t) of the RHB structure. Since a saturation magnetization, Ms, and thus, the Mr of the RHB is quite limited (e.g., as compared to the Ms of the soft bias), a thicker RHB is generally required to achieve the desired transverse bias field. The thicker RHB needed results in an increased topography along the reader stripe height (SH) direction. The large topography poses a challenge to TDMR DFL reader designs, as the large topography limits the read head's capacity in down track spacing (DTS), somewhat offsetting the intrinsic narrow shield-shield (S-S) advantage of DFL readers. A wide DTS can cause the two readers to become misaligned at large skew, thereby limiting the fraction of the disk accessible in TDMR mode. As such, the lower reader and the upper reader may perform asymmetrically with different performance and reliability.
[0005] A middle shield (MS) in TDMR read heads serves as both a bottom shield and a bottom lead for the upper reader (UR). The middle shield contributes to down track spacing (DTS) physically, UR performance stability magnetically, and lead resistance electrically. The large topography of the lower reader (LR) and deep over milling (OM) of the UR, specifically from a TDMR dual free layer (DFL) read head, result in an uneven middle shield with varying magnetic shield thicknesses. A single NiFe layer has currently been used for the MS and is not robust magnetically due to its uneven thickness and the nature of NiFe known intrinsically with more magnetic domain activities. While the topography of the LR needs to be improved, a MS with constant magnetic thickness and magnetic robustness has to be used with simplicity for implementation in TDMR read head fabrications.

[0006] Therefore, there is a need in the art for an improved TDMR read head.

SUMMARY OF THE DISCLOSURE

[0007] The present disclosure generally relates to a dual free layer (DFL) two dimensional magnetic recording (TDMR) read head. The read head comprises a first lower shield, a first sensor disposed over the first lower shield, a first upper shield disposed over the first sensor, a read separation gap (RSG) disposed on the first upper shield, a second lower shield disposed over the RSG, a second sensor disposed over the second lower shield, and a second upper shield disposed over the second sensor. In some embodiments, the second lower shield comprises a layer of CoFeHf. In another embodiment, the second lower shield comprises a first shield layer, a second shield layer, and a Ru layer disposed therebetween, where the first and second shield layers comprising CoFe and NiFe. In another embodiment, the second lower shield comprises a Ru layer, an IrMn layer, and a NiFe layer.

[0008] In one embodiment, a read head comprises a first lower shield, a first sensor disposed over the first lower shield, a second sensor disposed over the first sensor, a first upper shield disposed over the second sensor, and a middle shield disposed between the first sensor and the second sensor. The middle shield comprises a second upper shield disposed over the first sensor, a read separation gap disposed on the second upper shield, and a second lower shield disposed between the read separation gap and the second sensor, the second lower shield being a multilayer shield comprising a CoFe/Ru/CoFe anti-ferromagnetic coupling (AFC) layer or a Ru layer.

[0009] In another embodiment, a read head comprises a first lower shield, a first sensor disposed over the first lower shield, a first upper shield disposed over the first sensor, a read separation gap disposed on the first upper shield, the read separation gap being substantially planar, a second lower shield disposed over the read separation gap, the second lower shield comprising CoFeHf, a second sensor disposed over the second lower shield, and a second upper shield disposed over the second sensor.

[0010] In yet another embodiment, a read head comprises a first lower shield, a first dual free layer (DFL) sensor disposed over the first lower shield, a DFL second sensor disposed over the first DFL sensor, a first upper shield disposed over the second DFL sensor, and a substantially planar middle shield disposed between the first DFL sensor and the second DFL sensor. The substantially planar middle shield comprises a second upper shield disposed over the first DFL sensor, a read separation gap disposed on the second upper shield, a seed layer disposed on the read separation gap, the seed layer comprising Ru, NiFe, NiCr, SiO.sub.2, or combinations thereof, and a second lower shield disposed between and in contact with the seed layer and the second DFL sensor, the second lower shield being a multilayer shield comprising a first shield layer disposed on the seed layer, a CoFe/Ru/CoFe anti-ferromagnetic coupling (AFC) layer or a Ru layer disposed on the first shield layer, and a second shield layer disposed on the AFC layer or the Ru layer.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] So that the manner in which the above recited features of the present disclosure can be understood in detail, a more particular description of the disclosure, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only typical embodiments of this disclosure and are therefore not to be considered limiting of its scope, for the disclosure may admit to other equally effective embodiments.

[0012] FIG. **1** illustrates a disk drive embodying this disclosure.

[0013] FIG. **2** is a fragmented, cross-sectional side view through the center of a read/write head facing a magnetic media, according to one embodiment.

[0014] FIGS. **3**A-**3**B illustrate various views of a conventional dual free layer (DFL) read head comprising two sensors or readers, according to one embodiment.
[0015] FIGS. **4**A-**4**B illustrate various views of a DFL TDMR read head comprising two sensors or readers, according to various embodiments.
[0016] FIGS. **5**A-**5**D illustrate various embodiments of middle shields utilized in the read head of FIGS. **4**A-**4**B.
[0017] FIG. **6**A illustrates a chart comparing various middle shields, according to one embodiment.
[0018] FIG. **6**B illustrates a chart comparing a middle shield comprising CoFeHf to a conventional middle shield comprising only NiFe, according to one embodiment.
[0019] FIGS. **7**A-**7**C illustrate magnetic hysteresis (M-H) loops comparing the saturated magnetization (Bs) in nW versus the magnetic field in Oe, according to various embodiments.
[0020] To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures. It is contemplated that elements disclosed in one embodiment may be beneficially utilized on other embodiments without specific recitation.

DETAILED DESCRIPTION

[0021] In the following, reference is made to embodiments of the disclosure. However, it should be understood that the disclosure is not limited to specific described embodiments. Instead, any combination of the following features and elements, whether related to different embodiments or not, is contemplated to implement and practice the disclosure. Furthermore, although embodiments of the disclosure may achieve advantages over other possible solutions and/or over the prior art, whether or not a particular advantage is achieved by a given embodiment is not limiting of the disclosure. Thus, the following aspects, features, embodiments and advantages are merely illustrative and are not considered elements or limitations of the appended claims except where explicitly recited in a claim(s). Likewise, reference to "the disclosure" shall not be construed as a generalization of any inventive subject matter disclosed herein and shall not be considered to be an element or limitation of the appended claims except where explicitly recited in a claim(s).
[0022] The present disclosure generally relates to a dual free layer (DFL) two dimensional magnetic recording (TDMR) read head. The read head comprises a first lower shield, a first sensor disposed over the first lower shield, a first upper shield disposed over the first sensor, a read separation gap (RSG) disposed on the first upper shield, a second lower shield disposed over the RSG, a second sensor disposed over the second lower shield, and a second upper shield disposed over the second sensor. In some embodiments, the second lower shield comprises a layer of CoFeHf. In another embodiment, the second lower shield comprises a first shield layer, a second shield layer, and a Ru layer disposed therebetween, where the first and second shield layers comprising CoFe and NiFe. In another embodiment, the second lower shield comprises a Ru layer, an IrMn layer, and a NiFe layer.
[0023] FIG. **1** illustrates a disk drive **100** embodying this disclosure. As shown, at least one rotatable magnetic media **112** is supported on a spindle **114** and rotated by a disk drive motor **118**. The magnetic recording on each disk is in the form of any suitable patterns of data tracks, such as annular patterns of concentric data tracks (not shown) on the magnetic media **112**.
[0024] At least one slider **113** is positioned near the magnetic media **112**, each slider **113** supporting one or more magnetic head assemblies **121**. As the magnetic media rotates, the slider **113** moves radially in and out over the media surface **122** so that the magnetic head assembly **121** may access different tracks of the magnetic media **112** where desired data are written. Each slider **113** is attached to an actuator arm **119** by way of a suspension **115**. The suspension **115** provides a slight spring force which biases the slider **113** toward the media surface **122**. Each actuator arm **119** is attached to an actuator means **127**. The actuator means **127** as shown in FIG. **1** may be a voice coil motor (VCM). The VCM includes a coil movable within a fixed magnetic field, the direction and speed of the coil movements being controlled by the motor current signals supplied by control unit

129.

[0025] During operation of the disk drive **100**, the rotation of the magnetic media **112** generates an air bearing between the slider **113** and the media surface **122** which exerts an upward force or lift on the slider **113**. The air bearing thus counter-balances the slight spring force of suspension **115** and supports slider **113** off and slightly above the media **112** surface by a small, substantially constant spacing during normal operation. In the case of EAMR, a DC magnetic field generated from an assist element of the magnetic head assembly **121** enhances the write-ability so that the write element of the magnetic head assembly **121** may efficiently magnetize the data bits in the media **112**.

[0026] The various components of the disk drive **100** are controlled in operation by control signals generated by control unit **129**, such as access control signals and internal clock signals. Typically, the control unit **129** comprises logic control circuits, storage means, and a microprocessor. The control unit **129** generates control signals to control various system operations, such as drive motor control signals on line **123** and head position and seek control signals on line **128**. The control signals on line **128** provide the desired current profiles to optimally move and position slider **113** to the desired data track on media **112**. Write and read signals are communicated to and from write and read heads on the assembly **121** by way of recording channel **125**.

[0027] The above description of a typical magnetic disk storage system and the accompanying illustration of FIG. **1** are for representation purposes only. It should be apparent that disk storage systems may contain a large number of disks and actuators, and each actuator may support a number of sliders.

[0028] It is to be understood that the embodiments discussed herein are applicable to a data storage device such as a hard disk drive (HDD) as well as a tape drive such as a tape embedded drive (TED) or an insertable tape media drive, such as those conforming to the LTO (Linear Tape Open) standards. An example TED is described in co-pending patent application titled “Tape Embedded Drive,” U.S. application Ser. No. 16/365,034, filed Mar. 31, 2019, assigned to the same assignee of this application, which is herein incorporated by reference. As such, any reference in the detailed description to an HDD or tape drive is merely for exemplification purposes and is not intended to limit the disclosure unless explicitly claimed. For example, references to disk media in an HDD embodiment are provided as examples only, and can be substituted with tape media in a tape drive embodiment. Furthermore, reference to or claims directed to magnetic recording devices or data storage devices are intended to include at least both HDD and tape drive unless HDD or tape drive devices are explicitly claimed.

[0029] FIG. **2** is a fragmented, cross sectional side view through the center of a read/write head **200** facing the magnetic media **112**, according to one embodiment. The read/write head **200** may correspond to the magnetic head assembly **121** described in FIG. **1**. The read/write head **200** includes a media facing surface (MFS) **212**, such as an air bearing surface (ABS), a magnetic write head **210**, and a magnetic read head **211**, and is mounted such that the MFS **212** is facing the magnetic media **112**. The read/write head **200** may be an energy-assisted magnetic recording (EAMR) head or a perpendicular magnetic recording (PMR) head. In FIG. **2**, the magnetic media **112** moves past the write head **210** in the direction indicated by the arrow **232** and the read/write head **200** moves in the direction indicated by the arrow **234**.

[0030] In some embodiments, the magnetic read head **211** is a SOT differential reader **204** located between the shields S**1** and S**2**. In other embodiments, the magnetic read head **211** is a magnetoresistive (MR) read head that includes an MR sensing element **204** located between MR shields S**1** and S**2**. In some other embodiments, the magnetic read head **211** is a magnetic tunnel junction (MT)) read head that includes a MTJ sensing element **204** located between MR shields S**1** and S**2**. The magnetic fields of the adjacent magnetized regions in the magnetic media **112** are detectable by the MR (or MTJ) sensing element **204** as the recorded bits.

[0031] The write head **210** includes a return pole **206**, a main pole **220**, a trailing shield **240**, and a coil **218** that excites the main pole **220**. The coil **218** may have a "pancake" structure which winds around a back-contact between the main pole **220** and the return pole **206**, instead of a "helical" structure shown in FIG. **2**. A trailing gap (not shown) and a leading gap (not shown) may be in contact with the main pole and a leading shield (not shown) may be in contact with the leading gap. A recording magnetic field is generated from the main pole **220** and the trailing shield **240** helps making the magnetic field gradient of the main pole **220** steep. The main pole **220** may be a magnetic material such as a FeCo alloy. The main pole **220** may include a trailing surface **222** which may be parallel to a leading surface **236** of the trailing shield **240**. The main pole **220** may be a tapered write pole (TWP) with a trailing edge taper (TET) configuration. In one embodiment, the main pole **220** has a saturated magnetization (Ms) of 2.4 T and a thickness of about 300 nanometers (nm). The main pole **220** may comprise ferromagnetic materials, typically alloys of one or more of Co, Fe, and Ni. The trailing shield **240** may be a magnetic material such as NiFe alloy. In one embodiment, the trailing shield **240** has an Ms of about 1.2 T to about 1.6 T.

[0032] FIGS. **3**A-**3**B illustrate various views of a conventional dual free layer (DFL) two dimensional magnetic recording (TDMR) read head **300** comprising two sensors or readers **302**, **304**, according to one embodiment. FIG. **3**A illustrates a media facing surface (MFS) view of the DFL TDMR read head **300**, and FIG. **3**B illustrates a cross-sectional view of the DFL TDMR read head **300**.

[0033] The DFL TDMR read head **300** comprises a first lower shield **306**, a first insulation layer **308** disposed on the first shield **306**, a first sensor or reader **302** disposed on the first lower shield **306** between portions of the first insulation layer **308**, a first upper shield **312** disposed over the first sensor **302**, a read separation gap (RSG) **316** disposed on the first upper shield **312**, a second lower shield **318** disposed on the RSG **316**, a second insulation layer **320** disposed on the second lower shield **318**, a second sensor or reader **304** disposed on the second lower shield **318** between portions of the second insulation layer **320**, and a second upper shield **324** disposed over the second sensor **304**. The RSG **316** may comprise AlOx, where x is an integer greater than or equal to 1. The first and second sensors **302**, **304** may each individually be tunnel magnetoresistance (TMR) sensors or magnetic tunnel junction (MTJ) sensors. The first and second sensors **302**, **304** may be interchangeably referred to as a first reader **302** and a second reader **304** throughout.

[0034] The first reader **302** comprises a seed layer **330***a*, a first free layer **332***a* disposed on the seed layer **330***a*, a barrier layer **334***a* disposed on the first free layer **332***a*, a second free layer **336***a* disposed on the barrier layer **334***a*, and a cap layer **338***a* disposed on the second free layer **336***a*. The second reader **304** comprises a seed layer **330***b*, a first free layer **332***b* disposed on the seed layer **330***b*, a barrier layer **334***b* disposed on the first free layer **332***b*, a second free layer **336***b* disposed on the barrier layer **334***b*, and a cap layer **338***b* disposed on the second free layer **336***b*.

[0035] A first soft bias layer **310** is disposed on the first insulation layer **308** for the first reader **302** and an anti-ferromagnetically coupled (AFC) layer **314***a* is disposed between the first soft bias layer **310** and a second soft bias layer **311**. Similarly, a first soft bias layer **322** is disposed on the first insulation layer **320** for the second reader and an AFC layer **314***b* is disposed between the first soft bias layer **322** and a second soft bias layer **323**. The first upper shield **312** and the second upper shield **324** may each individually comprise a magnetic material similar to the soft bias material, such as NiFe, NiFe/CoFe laminates, NiFe/NiFeCr laminates, or NiFe/W laminates, for example ("/" as used here denotes separate layers in a multi-layer stack). The first upper shield **312** and the second upper shield **324** may also each individually comprise a magnetic material similar to the soft bias material exchange biased by an antiferromagnet, such as IrMn, IrCrMn. The first upper shield **312** and the second upper shield **324** connect seamlessly to the second soft bias layers **311**, **323**, respectively. The first insulation layer **308** extends in the y-direction on each side of the first sensor **302** to prevent the first sensor **302** from contacting the first soft bias layer **310**, the AFC layer **314***a*, and the second soft bias layer **311**. Similarly, the first insulation layer **320** extends in the y-direction on each side of the second sensor **304** to prevent the second sensor **304** from contacting the second soft bias layer **322**, and the AFC layer **314***b*, and the second soft bias layer **323**. The AFC layers **314***a* and **314***b* comprise a CoFe/Ru/CoFe tri-layer.

[0036] As shown in FIG. **3**B, a down-track spacing (DTS) **340** between the first barrier layer **334***a* of the first sensor **302** and the second barrier layer **334***b* of the second sensor **304** is about 90 nm to about 95 nm. A first rear hard bias (RHB) structure **342***a* is disposed behind the first reader **302**, recessed from the MFS in the z-direction. A second insulation layer **366***a* is disposed between the first RHB structure **342***a* and the first reader **302**, and between the first RHB structure **342***a* and the first lower shield **306**. A third insulation layer **344***a* is disposed behind the first RHB structure **342***a*. The first RHB structure **342***a* and the second insulation layer **366***a* extend above the first sensor **302** a distance **354** in the y-direction of about 10 nm to about 15 nm. The first RHB structure **342***a* and the second insulation layer **366***a* extend below the first sensor **302** a distance **352** in the −y-direction of about 5 nm to about 10 nm. The first, second, and third, insulation layers **308**, **366***a*, and **344***a* may each individually comprise MgO, AlOx, SiNx, SiOx and their laminates, where x is an integer greater than or equal to 1.

[0037] A second RHB structure **342***b* is disposed behind the second reader **304**, recessed from the MFS in the z-direction. A second insulation layer **366***b* is disposed between the second RHB structure **342***b* and the second reader **304**, and between the second RHB structure **342***b* and the second lower shield **318**. The third insulation layer **344***b* is disposed behind the first RHB structure **342***b*. The second RHB structure **342***b* extends below the second sensor **304** a distance **356** in the −y-direction of about 5 nm to about 10 nm. The first RHB structure **342***a* and the second insulation layer **366***a* extending above the first sensor **302** the distance **354**, and the second RHB structure **342***b* extending below the second sensor **304** the distance **356**, causes the DTS between the sensors **302**, **304** to widen in the y-direction.

[0038] Because the first RHB structure **342***a* and the second insulation layer **366***a* extend above the first sensor **302** the distance **354**, neither the RSG **316** nor the first upper shield **312** is linear in the z-direction. As a result, the RSG **316** comprises a first portion **316***a* disposed at the MFS extending in the z-direction, a second portion **316***b* extending in the yz-direction, and a third portion **316***c* extending in the z-direction that is unaligned with the first portion **316***a* in the y-direction. Similarly, the first upper shield **312** comprises a first portion **312***a* disposed at the MFS extending in the z-direction, a second portion **312***b* extending in the yz-direction, and a third portion **312***c* extending in the z-direction that is unaligned with the first portion **312***a* in the y-direction. Additionally, the second lower shield **318** varies in thickness in the y-direction. A first portion **318***a* of the second lower shield **318** aligned with the second sensor **304** in the y-direction has a first thickness **360** of about 30 nm to about 35 nm greater than a second thickness **358** of about 10 nm to about 15 nm of a second portion **318***b* of the second lower shield **318** disposed between the RSG **316** and the second insulation layer **366***b*.

[0039] FIGS. **4**A-**4**B illustrate various views of a DFL TDMR read head **400** comprising two sensors or readers **302**, **304**, according to one embodiment. FIG. **4**A illustrates an MFS view of the DFL TDMR read head **400**, and FIG. **4**B illustrates a cross-sectional view of the DFL TDMR read head **400**. The DFL TDMR read head **400** of FIGS. **4**A-**4**B may be within the disk drive **100** of FIG. **1**. The DFL TDMR read head **400** of FIGS. **4**A-**4**B may be the magnetic read head **211** of FIG. **2**. The DFL TDMR read head **400** is similar to the DFL TDMR read head **300** of FIGS. **3**A-**3**B; however the first RHB structure **442***a*, the second insulation layer **466***a*, the first upper shield **412**, the RSG **416**, the second lower shield **418**, the second RHB structure **442***b*, and the second insulation layer **466***b* vary. The first upper shield **412**, the RSG **416**, the second lower shield **418** may collectively be referred to herein as middle shields **415**.

[0040] Like the DFL TDMR read head **300** of FIGS. **3**A-**3**B, the DFL TDMR read head **400** comprises the first sensor or reader **302** and the second sensor or reader **304**. A first upper shield **412** is disposed over the first reader **302** and the second soft bias layer **311**. As shown in FIG. **4**B, a first surface **443***a* of the first RHB structure **442***a* disposed adjacent to the first upper shield **412** is substantially flush or aligned with a first surface **402***a* of the first reader **302**. In other words, the first RHB structure **442***a* and the second insulating layer **466***a* are substantially flush or aligned with the top surface **402***a* of the cap layer **338***a* of the first sensor **302** in the z-direction. Similarly, a first surface **443***b* of the second RHB structure **442***b* is substantially flush or aligned with a first surface **404***a* of the second reader **304** in the z-direction. In other words, the second RHB structure **442***b* is substantially flush or aligned with the bottom surface **404***a* of the seed layer **330***b* of the second sensor **304** in the z-direction.

[0041] Rather than the first RHB structure **442***a* extending above the first reader **302** in the y-direction, the first RHB structure **442***a* is recessed further into the first lower shield **306** in the −y-direction than the first RHB structure **342***a* of the DFL TDMR read head **300** of FIGS. **3**A-**3**B. The first RHB structure **442***a* of the read head **400** is recessed into the first lower shield **306** a distance **452** of about 15 nm to about 20 nm, which is greater than the distance **352** of FIGS. **3**A-**3**B. Because the first RHB structure **442***a* is substantially flush or aligned with the first reader **302**, the first upper shield **412** and the RSG **416** of the DFL TDMR read head **400** each extends substantially linearly along the z-axis from the MFS into the read head **400** such that the first upper shield **412** and the RSG **416** are planar.

[0042] Additionally, because the first upper shield **412** and the RSG **416** of the DFL TDMR read head **400** are each planar or extend substantially linearly along the z-axis, the second lower shield **418** comprises only two portions. As shown in FIG. **4**B, a first portion **419***a* of the second lower shield **418** disposed at the MFS adjacent to the second reader **304** has a first thickness **460** in the y-direction of about 20 nm to about 30 nm, and a second portion **419***b* of the second lower shield **418** disposed between the RSG **416** and the second insulation layer **444***b* has a second thickness **458** in the y-direction of greater than or equal to about 10 nm, such as about 15 nm to about 20 nm.

[0043] Comparing the second lower shield **418** of the read head **400** to the second lower shield **318** of the read head **300**, the first thickness **360** of the first portion **318***a* of the second lower shield **318** of the read head **300** and the second thickness **358** of the second portion **318***b* of the second lower shield **318** of the read head **300** differ in thickness by about 15 nm to about 25 nm. However, the first portion **419***a* and the second portion **419***b* of the second lower shield **418** of the read head **400** only differ in thickness by about 5 nm to about 10 nm. As such, the DTS **440** between the first sensor **302** and the second sensor **304** in the read head **400** is between about 75 nm to about 85 nm, which is less than the DTS **340** of the DFL TDMR read head **300** of FIGS. **3**A-**3**B.

[0044] Because the first surface **443***a* of the first RHB structure **442***a* is aligned with the first surface **402***a* of the first sensor **302**, and because the first surface **443***b* of the second RHB structure **442***b* is aligned with the first surface **404***a* of the second sensor **304**, the first and second sensors or readers **302**, **304** are physically asymmetric, where a bulk or majority of the first RHB structure **442***a* is disposed below (i.e., the −y-direction) the first sensor **302**, and where a bulk or majority of the second RHB structure **442***b* is disposed above (i.e., the y-direction) the second sensor **304**. As such, the DTS **440** between the first and second readers **302**, **304** is decreased, enabling a larger fraction of the disk to be operated in TDMR mode hence improving the performance and reliability, both magnetically and electronically, of the read head **400**.

[0045] FIGS. **5**A-**5**D illustrate MFS views of various embodiments of middle shields **415***a*, **415***b*, **415***c*, **415***d* utilized in the read head **400** of FIGS. **4**A-**4**B. Each middle shield **415***a*, **415***b*, **415***c*, **415***d* of FIGS. **5**A-**5**D may be individually used as the middle shield **415** in the read head **400** of FIGS. **4**A-**4**B. While not shown in FIGS. **5**A-**5**D, each middle shield **415***a*, **415***b*, **415***c*, **415***d* may further comprise the first upper shield **412** of FIGS. **4**A-**4**B disposed below the RSG **416**. In some embodiments, each middle shield **415***a*, **415***b*, **415***c*, **415***d* may be the second lower shield **418** of the read head **400** of FIGS. **4**A-**4**B.

[0046] The middle shield **415***a* of FIG. **5**A illustrates an embodiment of a pinned middle shield **415***a*. The pinned middle shield **415***a* comprises the RSG **416**, a middle shield (MS) seed layer **417** disposed on the RSG **416**, and a multilayer shield **418***a* disposed on the MS seed layer **417**. The multilayer shield **418***a* may be the second lower shield **418** of FIGS. **4**A-**4**B. The RSG **416** may comprise Al.sub.2O.sub.3. The MS seed layer **417** may comprise two layers, an underlayer serving as chemical mechanical polishing (CMP) stopping layer during the planarization post MS seed depositions, and a seed layer composed of magnetic or non-magnetic metallic materials. A Ru/NiFe bilayer is used as a MS seed layer **417** in one embodiment, where Ru is used as an underlayer and NiFe is used as is the seed layer. The underlayer of the MS seed layer **417** can also be Ru and/or SiO.sub.2, and may have a thickness in the y-direction of about 20 Å to about 30 Å. The seed layer of the MS seed layer **417** can also be NiFe and/or NiCr, and may have a thickness in the y-direction of about 80 Å to about 150 Å. In some embodiments, the MS seed layer **417** may be considered part of the multilayer shield **418***a*.

[0047] The multilayer shield **418***a* comprises a seed layer **550** disposed on the MS seed layer **417**, an antiferromagnetic (AFM) layer **552** disposed on the seed layer **550**, and a pinned layer **554** disposed on the AFM layer **552**. The seed layer **550** comprises Ta, Ru, NiCr, or NiFe, or combinations thereof, the AFM layer **552** comprises IrMn, and the pinned layer **554** comprises NiFe, Co, CoFe, or combinations thereof. The seed layer **550** has a thickness **556** in the y-direction of about 15 Å to about 30 Å, the AFM layer **552** has a thickness **558** in the y-direction of about 40 Å to about 60 Å, and the pinned layer **554** has a thickness **560** in the y-direction of about 150 Å to about 300 Å.

[0048] The middle shield **415***b* of FIG. **5**B comprises the RSG **416**, the MS seed layer **417** disposed on the RSG **416**, and a shield **418***b* disposed on the MS seed layer **417**. The shield **418***b* may be the second lower shield **418** of FIGS. **4**A-**4**B. The RSG **416** may comprise Al.sub.2O.sub.3. The MS seed layer **417** may comprise a Ru/NiFe bilayer in one embodiment, and a NiCr single layer in another embodiment. The thickness of the MS seed layer **417** may have a thickness in the y-direction of about 50 Å to about 150 Å. In some embodiments, the MS seed layer **417** may be considered part of the shield **418***b*. As a comparison, a shield (like the shield **418***b* shown) comprises NiFe in prior art. The shield **418***b* can also comprise CoFeHf in another embodiment. The shield **418***b* has a thickness **562** in the y-direction of about 200 Å to about 250 Å. CoFeHf is magnetically soft due to being amorphous or microcrystalline in nature. CoFeHf has a high anisotropic magnetic field (Hk). For example, as shown below in the chart **650** of FIG. **6**B, CoFeHf has a Hk of about 63 Oe, whereas NiFe has a Hk of about 4 Oe.

[0049] The middle shield **415***c* of FIG. **5**C comprises the RSG **416**, the MS seed layer **417** disposed on the RSG **416**, and a synthetic antiferromagnetic (SAF) multilayer shield **418***c* disposed on the MS seed layer **417**. The multilayer shield **418***c* may be the second lower shield **418** of FIGS. **4**A-**4**B. The RSG **416** may comprise Al.sub.2O.sub.3. The MS seed layer **417** may comprise Ru/NiFe, Ru/NiCr, SiO.sub.2/NiFe, or SiO.sub.2/NiCr bilayers, or NiCr as a single layer. The Ru or SiO.sub.2 underlayer of the MS seed layer **417** may have a thickness in the y-direction of about 20 Å to about 30 Å, and the NiFe or NiCr seed layer of the MS seed layer **417** may have a thickness in the y-direction of about 40 Å to about 70 Å. In some embodiments, the MS seed layer **417** may be considered part of the multilayer shield **418***c*.

[0050] The multilayer shield **418***c* comprises a first shield layer (SL1) **564**, an anti-ferromagnetic coupling (AFC) layer or a single Ru layer **566** disposed on the first shield layer **564**, and a second shield layer (SL2) **568** disposed on the AFC layer or the Ru layer **566**. The SL1 **564** comprises NiFe, CoFe, and/or combinations thereof, and has a total thickness **570** in the y-direction of about 40 Å to about 60 Å. The layer **566** comprises an AFC CoFe/Ru/CoFe trilayer, or a Ru single layer and has a thickness **572** in the y-direction of about 28 Å, with about 10 Å for each CoFe layer, and about 8 Å for the Ru layer. The SL2 **568** comprises NiFe, CoFe, and combinations thereof, and has a total thickness **574** in the y-direction of about 150 Å to about 200 Å.

[0051] The middle shield **415***d* of FIG. **5**D comprises the RSG **416**, the MS seed layer **417** disposed on the RSG **416**, and a SAF multilayer shield **418***d* disposed on the MS seed layer **417**. The multilayer shield **418***d* may be the second lower shield **418** of FIGS. **4**A-**4**B. The RSG **416** may comprise Al.sub.2O.sub.3. The MS seed layer **417** may comprise Ru/NiFe, Ru/NiCr, SiO.sub.2/NiFe, or SiO.sub.2/NiCr bilayers, or a NiCr single layer. The Ru or SiO.sub.2 underlayer of the MS seed layer **417** may have a thickness in the y-direction of about 20 Å to 30 Å, and the NiFe or NiCr seed layer of the MS seed layer **417** may have a thickness in the y-direction of about 40 Å to about 70 Å. In some embodiments, the MS seed layer **417** may be considered part of the multilayer shield **418***d*.

[0052] The multilayer shield **418***d* comprises a first shield layer (SL1) **576**, an anti-ferromagnetic coupling (AFC) layer or a single Ru layer **578** disposed on the first shield layer **576**, and a second shield layer (SL2) **580** disposed on the AFC layer or the Ru layer **578**. The SL1 **576** comprises NiFe, CoFe, and/or combinations thereof, and has a total thickness **582** in the y-direction of about 90 Å to about 110 Å. The layer **578** comprises an AFC CoFe/Ru/CoFe trilayer or a Ru single layer, and has a thickness **584** in the y-direction of about 28 Å, with about 10 Å for each CoFe layer and about 8 Å for the Ru layer. The SL2 **580** comprises NiFe, CoFe, and/or combinations thereof, and has a total thickness **586** in the y-direction of about 120 Å to about 160 Å. The multilayer shield **418***d* of FIG. **5**D varies from the multilayer shield **418***c* of FIG. **5**C in that the SL1 **576** of multilayer shield **418***d* is much larger than the SL1 **564**, where the thickness **582** of the SL1 **576** of multilayer shield **418***d* is about equal to the thickness **586** of the SL2 **580**.

[0053] Each middle shield **415***a*, **415***b*, **415***c*, and **415***d* of FIGS. **5**A-**5**D is magnetically robust and have a high magnetic anisotropy. Multilayer shields **415***c* and **415***d* are two variations from one embodiment of a SAF middle shield with different AFC positions or Ru positions along the y-direction. As such, read heads utilizing one of the middle shields **415***a*, **415***b*, **415***c*, and **415***d* have improved signal to noise ratios, error rates and higher areal density capacities (ADC).

[0054] FIG. **6**A illustrates a chart **600** comparing various SAF middle shields **602**, **604**, **606**, **608**, **610**, according to one embodiment, with the middle shield seed layer being considered part of the middle shields. Each of the middle shields **602**, **604**, **606**, **608**, **610** shown in the chart **600** may be individually utilized in the read head **400** of FIGS. **4**A-**4**B.

[0055] The chart **600** compares various different embodiments of middle shields **602-610** that are each magnetically robust and have a high magnetic anisotropy. In each middle shield **602-610**, the first Ru layer and a portion of the first NiFe layer may be the MS seed layer **417** of FIGS. **5**A-**5**D. Middle shields **602**, **606**, **608**, and **610** are similar; however, the thicknesses of the various NiFe layers within each vary.

[0056] The middle shield **602** comprises a first Ru layer of about 30 Å, a first NiFe layer of about 80 Å disposed on the first Ru layer, a first CoFe layer of about 10 Å disposed on the first NiFe layer, a second Ru layer of about 8 Å disposed on the first CoFe layer, a second CoFe layer of about 10 Å disposed on the second Ru layer, and a second NiFe layer of about 260 Å disposed on the second CoFe layer. The middle shield **602** may be the middle shield **415***c* of FIG. **5**C, where the second Ru layer is the Ru layer **566**. The middle shield **604** comprises a first Ru layer of about 30 Å, a first NiFe layer of about 110 Å disposed on the first Ru layer, a second Ru layer of about 8 Å disposed on the first NiFe layer, and a second NiFe layer of about 215 Å disposed on the second Ru layer.

[0057] The middle shield **606** comprises a first Ru layer of about 30 Å, a first NiFe layer of about 100 Å disposed on the first Ru layer, a first CoFe layer of about 10 Å disposed on the first NiFe layer, a second Ru layer of about 8 Å disposed on the first CoFe layer, a second CoFe layer of about 10 Å disposed on the second Ru layer, and a second NiFe layer of about 205 Å disposed on the second CoFe layer. The middle shield **608** comprises a first Ru layer of about 30 Å, a first NiFe layer of about 130 Å disposed on the first Ru layer, a first CoFe layer of about 10 Å disposed on the first NiFe layer, a second Ru layer of about 8 Å disposed on the first CoFe layer, a second CoFe layer of about 10 Å disposed on the second Ru layer, and a second NiFe layer of about 175 Å disposed on the second CoFe layer. The middle shield **610** comprises a first Ru layer of about 30 Å, a first NiFe layer of about 150 Å disposed on the first Ru layer, a first CoFe layer of about 10 Å disposed on the first NiFe layer, a second Ru layer of about 8 Å disposed on the first CoFe layer, a second CoFe layer of about 10 Å disposed on the second Ru layer, and a second NiFe layer of about 155 Å disposed on the second CoFe layer. The middle shield **610** may be the middle shield **415***d* of FIG. **5**D, where the second Ru layer is the Ru layer **578**.

[0058] In the chart **600**, column **612** identifies the middle shields **602-610**, column **614** shows the various film layers of each middle shield **602-610** and their respective thicknesses in Å, column **616** shows a change in thickness (ΔThk) in Å between the second and the first NiFe layers, column **618** shows the antiferromagnetic coupling strength (J.sub.Ru) in erg/cm.sup.2, and column **620** shows the net moment (Δm) between the second and the first NiFe layers in memu/cm.sup.2.

[0059] As shown in column **618**, middle shield **604**, which does not comprise any CoFe layers, has the lowest coupling strength of about 0.07 erg/cm.sup.2. However, middle shields **602**, **606**, **608**, and **610** all have relatively high coupling strengths of around 0.4 erg/cm.sup.2. Additionally, middle shield **610**, which has the lowest ΔThk also has the lowest Δm, whereas the middle shields **602**, **604**, and **606** each have a higher Δm and a higher ΔThk. The Δm or the ΔThk of the middle shield is not limited to only positive values, as described by afore-illustrated embodiments, and its value can also be zero or negative in some other embodiments.

[0060] FIG. **6**B illustrates a chart **650** comparing a middle shield comprising CoFeHf to a conventional middle shield comprising only NiFe, according to one embodiment. The middle shield comprising CoFeHf may be the middle shield **415***b* of FIG. **5**B. As shown in the chart **650**, post annealing of the read head, the middle shield comprising CoFeHf has a significantly higher high anisotropic magnetic field (Hk), about 63 Oe, than the middle shield comprising only NiFe, about 4 Oe.

[0061] FIGS. **7**A-**7**C illustrate magnetic hysteresis or magnetization versus magnetic field (M-H) loops **700**, **750**, **775** comparing the saturated magnetization (Bs) in nano Weber (nW) versus the magnetic field in Oe, according to various embodiments. The M-H loop **700** of FIG. **7**A illustrates a conventional middle shield comprising only NiFe, like discussed above in FIG. **6**B, the M-H loop **750** of FIG. **7**B illustrates the middle shields **600-610** of chart **600** of FIG. **6**A, and the M-H loop **775** illustrates the middle shield comprising CoFeHf, such as the middle shield **415***b* of FIG. **5**B.

[0062] As shown in the M-H loop **700**, when a magnetic field is applied, the magnetic response of the conventional middle shield comprising only NiFe is hysteretic along the easy axis and has a magnetic anisotropy field (Hk) about 5 Oe measured along the hard axis. Comparatively, each of the middle shields **602-610** shown in the M-H loop **750** have a non-hysteretic magnetic response with saturation at fields about −100 Oe or about 100 Oe in one embodiment, and about −1300 Oe or about 1300 Oe in other embodiments, and the middle shield comprising CoFeHf shown in the M-H loop **775** has a magnetic anisotropy field of about 60 Oe measured along the hard axis. Thus, each middle shield **602-610** and the middle shield comprising CoFeHf all achieve a higher magnetic anisotropy field than a conventional middle shield comprising only NiFe.

[0063] Thus, a middle shield comprising IrMn, a middle shield comprising CoFeHf, and a multilayer middle shield comprising a Ru layer are each magnetically robust and have a high magnetic anisotropy. As such, read heads utilizing one of such middle shields have improved signal to noise ratio, error rates and a higher ADC.

[0064] In one embodiment, a read head comprises a first lower shield, a first sensor disposed over the first lower shield, a second sensor disposed over the first sensor, a first upper shield disposed over the second sensor, and a middle shield disposed between the first sensor and the second sensor. The middle shield comprises a second upper shield disposed over the first sensor, a read separation gap disposed on the second upper shield, and a second lower shield disposed between the read separation gap and the second sensor, the second lower shield being a multilayer shield comprising a CoFe/Ru/CoFe anti-ferromagnetic coupling (AFC) layer or a Ru layer.

[0065] The second lower shield further comprises a first shield layer and a second shield layer, the AFC layer or the Ru layer being disposed between the first shield layer and the second shield layer.

The first shield layer and the second shield layer each individually comprises NiFe, CoFe, and combinations thereof. The second shield layer has a greater thickness than the first shield layer. The first shield layer has a thickness substantially equal to or smaller than the second shield layer. The second upper shield and the read separation gap are substantially planar, extending into the read head substantially perpendicular to a media facing surface. The second lower shield comprises the Ru layer, and the second lower shield further comprises an antiferromagnetic (AFM) layer disposed on the Ru layer, and a pinned layer disposed on the AFM layer. A thickness of the AFM layer is greater than a thickness of the Ru layer, and wherein a thickness of the pinned layer is greater than the thickness of the AFM layer. A magnetic recording device comprises the read head.
[0066] In another embodiment, a read head comprises a first lower shield, a first sensor disposed over the first lower shield, a first upper shield disposed over the first sensor, a read separation gap disposed on the first upper shield, the read separation gap being substantially planar, a second lower shield disposed over the read separation gap, the second lower shield comprising CoFeHf, a second sensor disposed over the second lower shield, and a second upper shield disposed over the second sensor.
[0067] The read head further comprises a seed layer disposed between the second lower shield and the read separation gap, the second lower shield having a greater thickness than the seed layer. The second lower shield comprises a layer of CoFeHf having a thickness of about 200 Å to about 300 Å. The first sensor and the second sensor are each a dual free layer sensor. The read head further comprises a first rear hard bias (RHB) structure disposed adjacent to the first sensor, the first sensor being disposed at a media facing surface (MFS) and the first RHB structure being recessed from the MFS, and a second RHB structure disposed adjacent to the second sensor, the second sensor being disposed at the MFS and the second RHB structure being recessed from the MFS. The first upper shield, the read separation gap, and the second lower shield are disposed between the first RHB structure and the second RHB structure. A magnetic recording device comprises the read head.
[0068] In yet another embodiment, a read head comprises a first lower shield, a first dual free layer (DFL) sensor disposed over the first lower shield, a DFL second sensor disposed over the first DFL sensor, a first upper shield disposed over the second DFL sensor, and a substantially planar middle shield disposed between the first DFL sensor and the second DFL sensor. The substantially planar middle shield comprises a second upper shield disposed over the first DFL sensor, a read separation gap disposed on the second upper shield, a seed layer disposed on the read separation gap, the seed layer comprising Ru, NiFe, NiCr, SiO.sub.2, or a combination thereof, and a second lower shield disposed between and in contact with the seed layer and the second DFL sensor, the second lower shield being a synthetic antiferromagnetic multilayer shield comprising a first shield layer disposed on the seed layer, a CoFe/Ru/CoFe anti-ferromagnetic coupling (AFC) layer or a Ru layer disposed on the first shield layer, and a second shield layer disposed on the AFC layer or the Ru layer.
[0069] The first shield layer and the second shield layer are each an individually single or multilayer structure comprising NiFe, CoFe, and combinations thereof with the middle shield seed being considered part of the first shield layer. A thickness of the AFC layer or the Ru layer is less than the thickness of the first shield layer. The AFC layer or the Ru layer has a thickness of about 8 Å, the first shield layer has a thickness of about 80 Å to about 160 Å, and the second shield layer has a thickness of about 160 Å to about 260 Å. A magnetic recording device comprises the read head.
[0070] While the foregoing is directed to embodiments of the present disclosure, other and further embodiments of the disclosure may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

Claims

1. A read head, comprising: a first lower shield; a first sensor disposed over the first lower shield; a first upper shield disposed over the first sensor; a read separation gap disposed on the first upper shield, the read separation gap being substantially planar; a second lower shield disposed over the read separation gap, the second lower shield comprising CoFeHf; a second sensor disposed over the second lower shield; and a second upper shield disposed over the second sensor.
2. The read head of claim 1, further comprising a seed layer disposed between the second lower shield and the read separation gap, the second lower shield having a greater thickness than the seed layer.
3. The read head of claim 1, wherein the second lower shield comprises a layer of CoFeHf having a thickness of about 200 Å to about 300 Å.
4. The read head of claim 1, wherein the first sensor and the second sensor are each a dual free layer sensor.
5. The read head of claim 1, further comprising: a first rear hard bias (RHB) structure disposed adjacent to the first sensor, the first sensor being disposed at a media facing surface (MFS) and the first RHB structure being recessed from the MFS; and a second RHB structure disposed adjacent to the second sensor, the second sensor being disposed at the MFS and the second RHB structure being recessed from the MFS.
6. The read head of claim 5, wherein the first upper shield, the read separation gap, and the second lower shield are disposed between the first RHB structure and the second RHB structure.
7. A magnetic recording device comprising the read head of claim 1.
8. A read head, comprising: a first lower shield; a first sensor disposed over the first lower shield; a first upper shield disposed over the first sensor; a read separation gap disposed on the first upper shield, the read separation gap being substantially planar; a seed layer disposed on the read separation gap, the seed layer comprising one of NiCr or a bilayer of Ru/NiFe; a second lower shield disposed over the read separation gap, the second lower shield comprising CoFeHf; a second sensor disposed over the second lower shield; and a second upper shield disposed over the second sensor.
9. The read head of claim 8, wherein the seed layer has a thickness of about 50 Å to about 150 Å, and wherein the second lower shield has a thickness of about 200 Å to about 250 Å.
10. The read head of claim 8, wherein the second lower shield has an anisotropic magnetic field of about 63 Hk.
11. The read head of claim 8, wherein the first sensor and the second sensor are each a dual free layer sensor.
12. The read head of claim 8, further comprising: a first rear hard bias (RHB) structure disposed adjacent to the first sensor, the first sensor being disposed at a media facing surface (MFS) and the first RHB structure being recessed from the MFS; and a second RHB structure disposed adjacent to the second sensor, the second sensor being disposed at the MFS and the second RHB structure being recessed from the MFS, wherein the first upper shield, the read separation gap, and the second lower shield are disposed between the first RHB structure and the second RHB structure.
13. The read head of claim 12, wherein the first RHB structure is recessed into the first lower shield a distance of about 15 nm to about 20 nm.
14. A magnetic recording device comprising the read head of claim 8.
15. A read head, comprising: a first lower shield; a first sensor disposed over the first lower shield; a first upper shield disposed over the first sensor; a read separation gap disposed on the first upper shield, the read separation gap being substantially planar; a seed layer disposed on the read separation gap, the seed layer comprising one of NiCr or a bilayer of Ru/NiFe; a second lower shield disposed over the read separation gap, the second lower shield comprising CoFeHf, wherein the second lower shield has an anisotropic magnetic field of about 63 Hk, and wherein the second lower shield has a greater thickness than the seed layer; a second sensor disposed over the second

lower shield; and a second upper shield disposed over the second sensor.

16. The read head of claim 15, wherein the seed layer has a thickness of about 50 Å to about 150 Å, and wherein the second lower shield has a thickness of about 200 Å to about 250 Å.

17. The read head of claim 15, further comprising: a first rear hard bias (RHB) structure disposed adjacent to the first sensor, the first sensor being disposed at a media facing surface (MFS) and the first RHB structure being recessed from the MFS; and a second RHB structure disposed adjacent to the second sensor, the second sensor being disposed at the MFS and the second RHB structure being recessed from the MFS, wherein the first upper shield, the read separation gap, and the second lower shield are disposed between the first RHB structure and the second RHB structure, and wherein the first RHB structure is recessed into the first lower shield a distance of about 15 nm to about 20 nm.

18. The read head of claim 15, wherein the read separation gap comprises Al.sub.2O.sub.3, and wherein the second lower shield has a greater thickness than the read separation gap.

19. The read head of claim 15, wherein the first sensor and the second sensor are each a dual free layer sensor.

20. A magnetic recording device comprising the read head of claim 15.