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Carey et al.

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(54) **MAGNETIC READ SENSOR EMPLOYING OBLIQUE ETCHED UNDERLAYERS FOR INDUCING UNIAXIAL MAGNETIC ANISOTROPY IN HARD MAGNETIC BIAS LAYERS**

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G11B 5/39 (2006.01)

(52) **U.S. Cl.** **360/324.12**; 360/324.2

(58) **Field of Classification Search** 360/324.12, 360/324.2

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,943,047	A	3/1976	Cruzan et al.	204/192
4,309,267	A	1/1982	Boyd et al.	204/298
5,143,794	A	9/1992	Suzuki et al.	428/611
5,759,682	A	6/1998	Ouchi et al.	428/332
5,815,343	A	9/1998	Ishikawa et al.	360/97.01
6,007,623	A	12/1999	Thiele et al.	117/95
6,086,974	A	7/2000	Thiele et al.	428/65.3
6,169,303	B1	1/2001	Anthony	257/295
6,278,595	B1 *	8/2001	Xue et al.	360/327.31
6,331,364	B1	12/2001	Baglin et al.	428/694 T
6,735,850	B1	5/2004	Gibbons et al.	29/603.07
6,743,529	B2	6/2004	Saito et al.	428/694 SG
7,342,752	B1 *	3/2008	Zhang et al.	360/324.12
2002/0051328	A1	5/2002	Hasegawa	360/322
2003/0030947	A1	2/2003	Ooshima	360/324.12
2005/0105223	A1 *	5/2005	Larson et al.	360/324.12

OTHER PUBLICATIONS

D. Sekiba, R. Moroni, G. Gonella, F. Buatier de Mongeot, C. Boragno, L. Mattera, and U. Valbusa, "Uniaxial magnetic anisotropy tuned by nanoscale ripple formation: Ion-sculpting of Co/Cu(001) thin films," Applied Physics Letters, vol. 84 No. 5, Feb. 2004.

(Continued)

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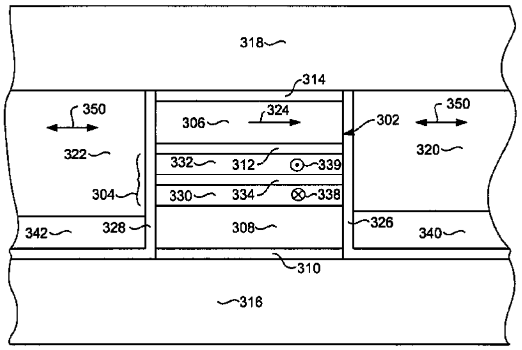
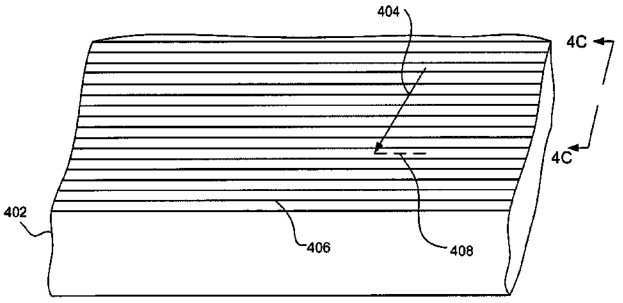
(57) **ABSTRACT**

A magnetoresistive sensor having a hard bias layer with an engineered magnetic anisotropy in a direction substantially parallel with the medium facing surface. The hard bias layer may be constructed of CoPt, CoPtCr or some other magnetic material and is deposited over an underlayer that has been ion beam etched. The ion beam etch has been performed at an angle with respect to normal in order to induce anisotropic roughness on its surface for example in form of oriented ripples or facets. The anisotropic roughness induces a uniaxial magnetic anisotropy substantially parallel to the medium facing surface in the hard magnetic bias layers deposited there over.

25 Claims, 8 Drawing Sheets





OTHER PUBLICATIONS

Dr. Chen Yunjie, "Highly Oriented Media for High Density Magnetic Recording," Storage Unlimited, Jul.-Sep. 2004.

S. Rusponi, G. Costantini, F. Buatier de Mongeot, C. Boragno, and U. Valbusa, "Patterning a surface on the nanometric scale by ion sputtering," Applied Physics Letters, vol. 75 No. 21, Nov. 1999.

J.E. Lee, Y. Roh, S.C. Oh, H.-J. Kim, Y.K. Ha, J.S. Bae, I.G. Baek, S.O. Park, U.-I. Chung. and J.T. Moon, "Improved Magnetic Tunnel Junction With Amorphous Seed Layer, Surface Treatment, and High-Polarization Magnetic Materials," IEEE Transactions on Magnetics, vol. 40, No. 4, Jul. 2004.

Jan-Ulrich Thiele, M.E. Best, M.F. Toney, D. Weller, "Grain Size Control in FePt Thin Films by Ar-Ion Etched Pt Seed Layers," IEEE Transactions on Magnetics, vol. 37, No. 4, Jul. 2001.

M. Takahashi, H. Shoji, D. D. Djayaprawira, and S. Yoshimura, "Novel Sputtering Process to Reduce the Grain Size and its Distribution in Co-Based Longitudinal Thin Film Media—New Seedlayer and High K_u^{Grain} Material," IEEE Transactions on Magnetics, vol. 36, No. 5, Sep. 2000.

T.C. Arnoldussen, E.M. Rossi, A. Ting, A. Brunsch, J. Schneider, and G. Trippel, "Obliquely Evaporated Iron-Cobalt and Iron-Cobalt-Chromium Thin Film Recording Media," IEEE Transactions on Magnetics, vol. 20, No. 5, Sep. 1984.

M.J. Hadley and R.J. Pollard, "Magnetic and Structural Properties of Co Films Deposited onto Obliquely Sputtered Pt Underlayers," Journal of Applied Physics, vol. 92, No. 12, Dec. 2002.

J.F. Whitacre, Z.U. Rek, J.C. Billello and S.M. Yalisove, "Surface Roughness and In-Plane Texturing in Sputtered Thin Films," Journal of Applied Physics, vol. 84, No. 3, Aug. 1998.

R. Moroni, D. Sekiba, F. Buatier de Mongeot, G. Gonella, C. Boragno, L. Mattera, and U. Valbusa, "Uniaxial Magnetic Anisotropy in Nanostructured Co/Cu(001): From Surface Ripples to Nanowires," Physical Review Letters, vol. 91, No. 16, Oct. 2003.

* cited by examiner

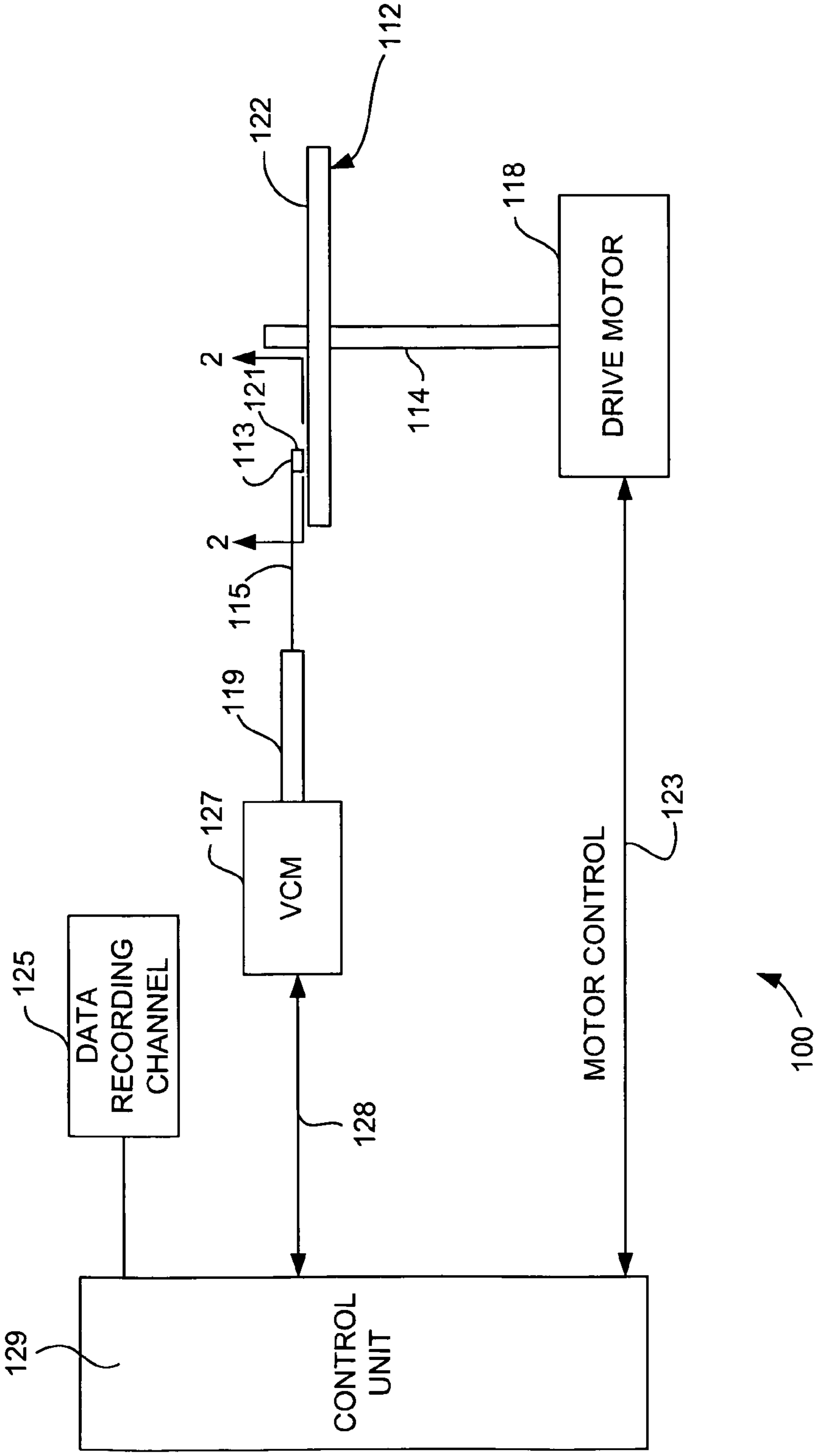

112
122
118
DRIVE MOTOR
114
2
121
113
2
115
119
127
VCM
125
DATA RECORDING CHANNEL
128
MOTOR CONTROL
123
100
129
CONTROL UNIT

FIG. 1

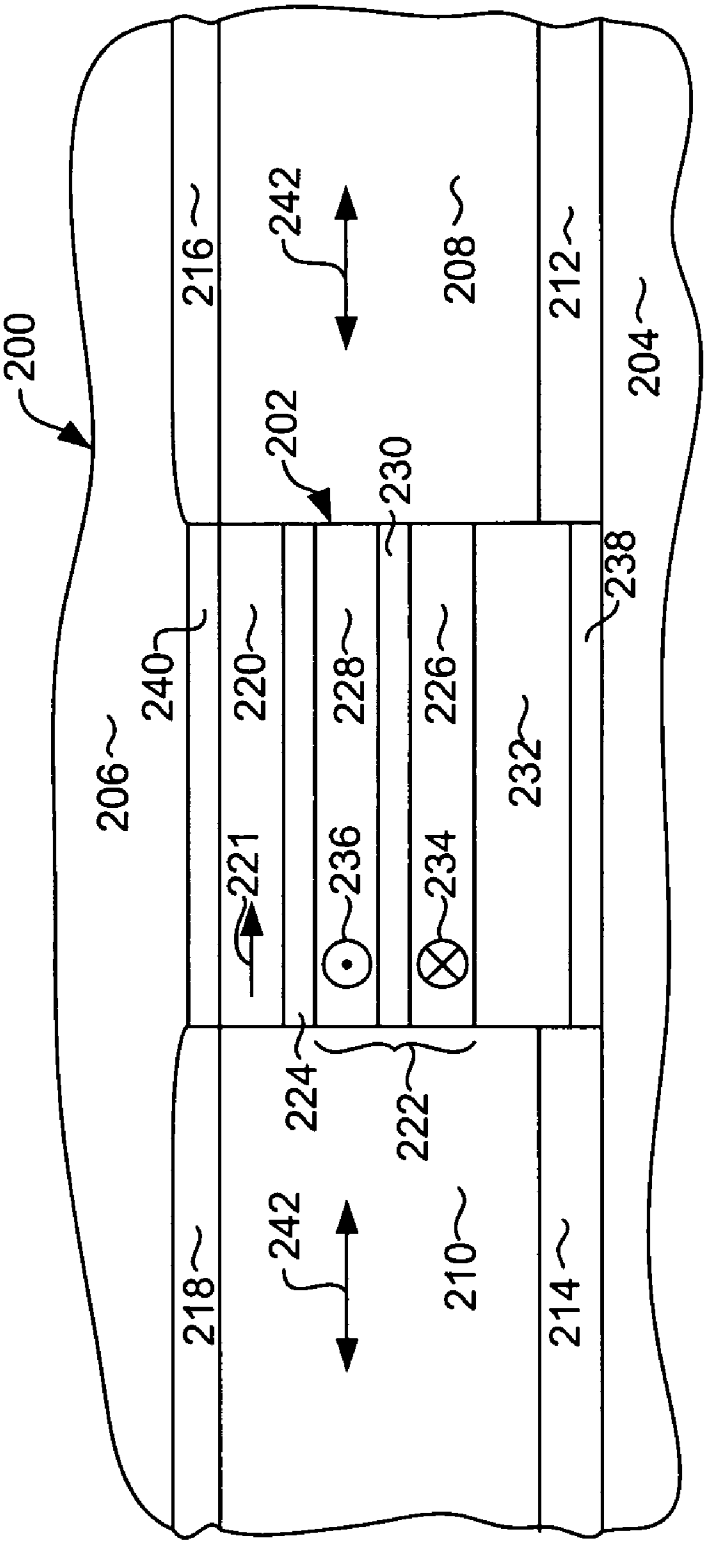

200
216
242
208
212
204
202
230
238
206
240
220
228
226
232
221
236
234
224
222
242
218
210
214

FIG. 2

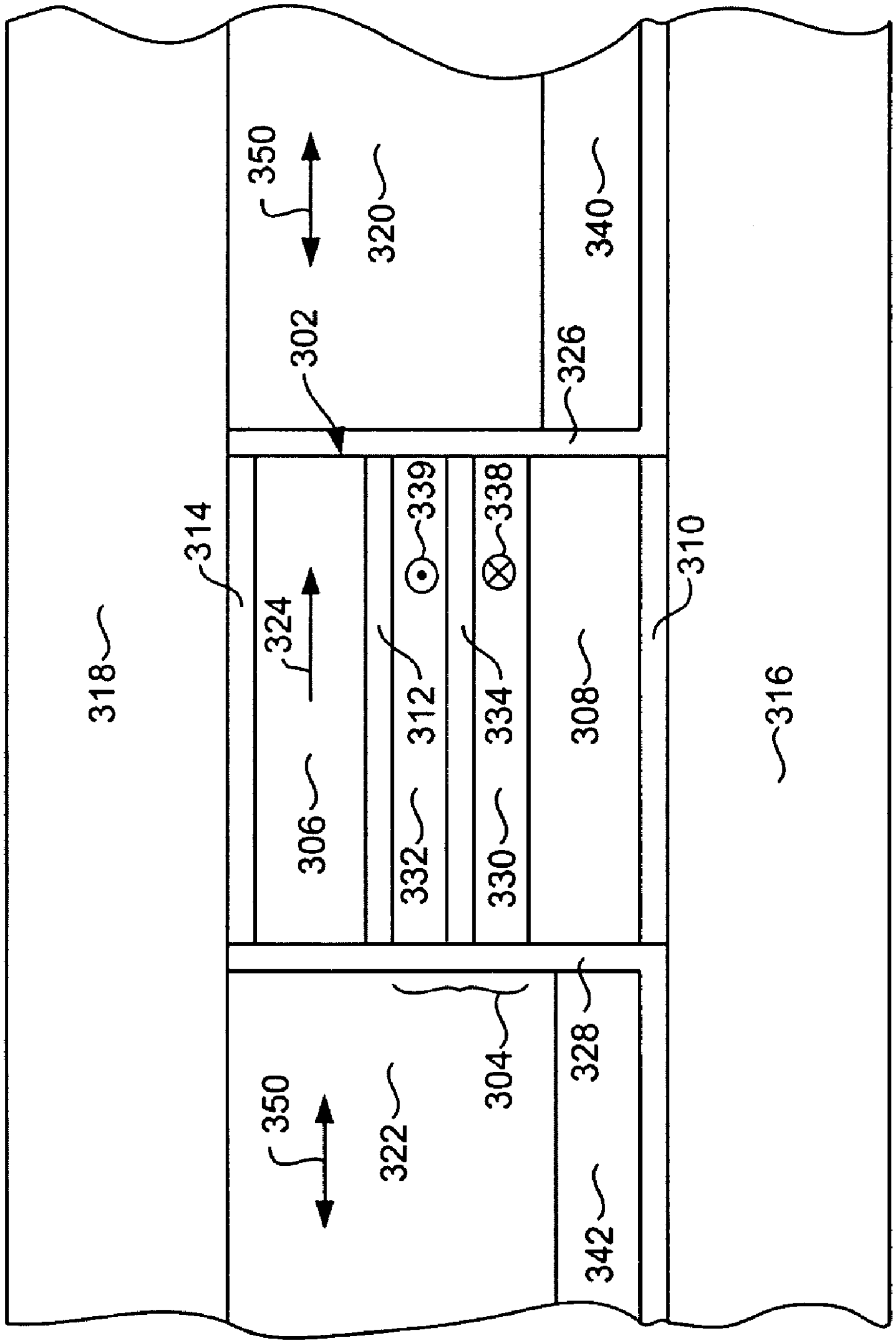

318
314
324
306
302
320
350
340
326
339
338
312
334
332
330
308
310
316
304
328
322
342
350

FIG. 3

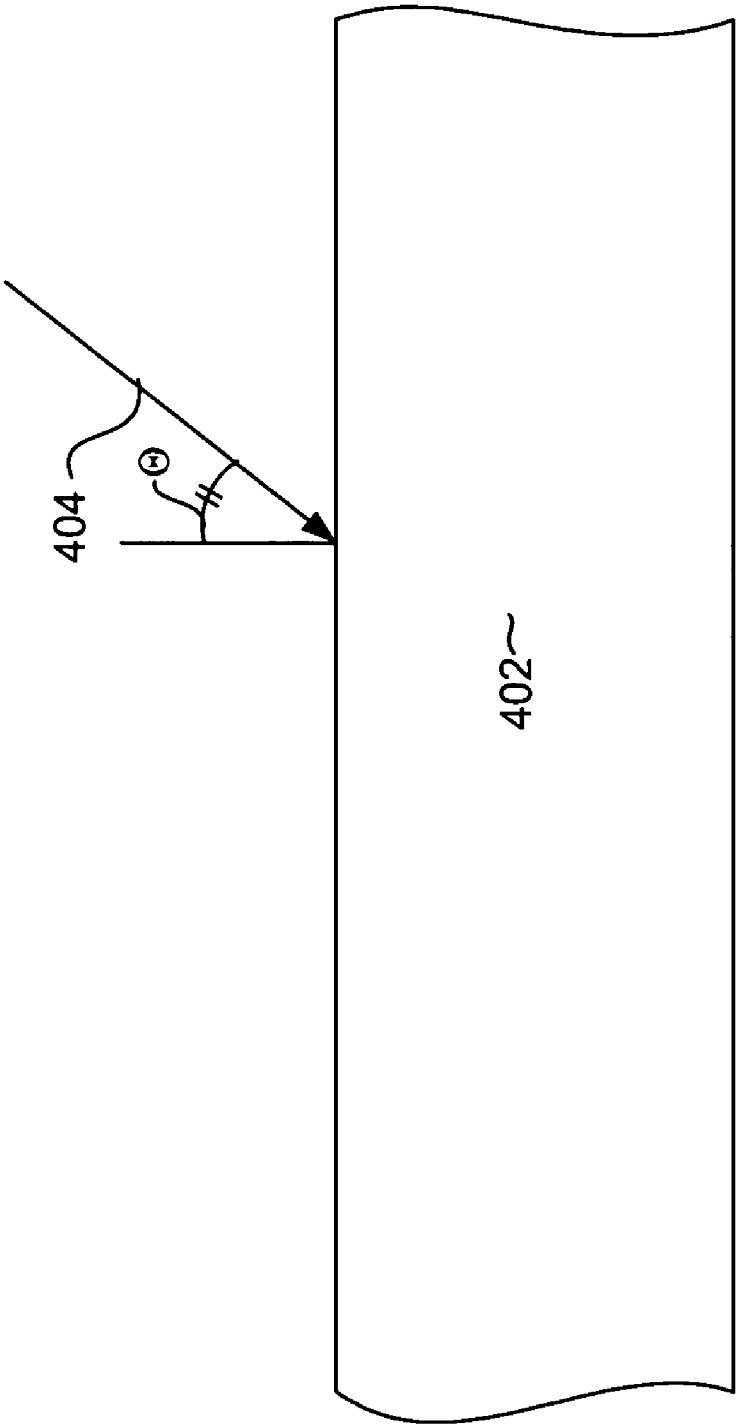


FIG. 4A

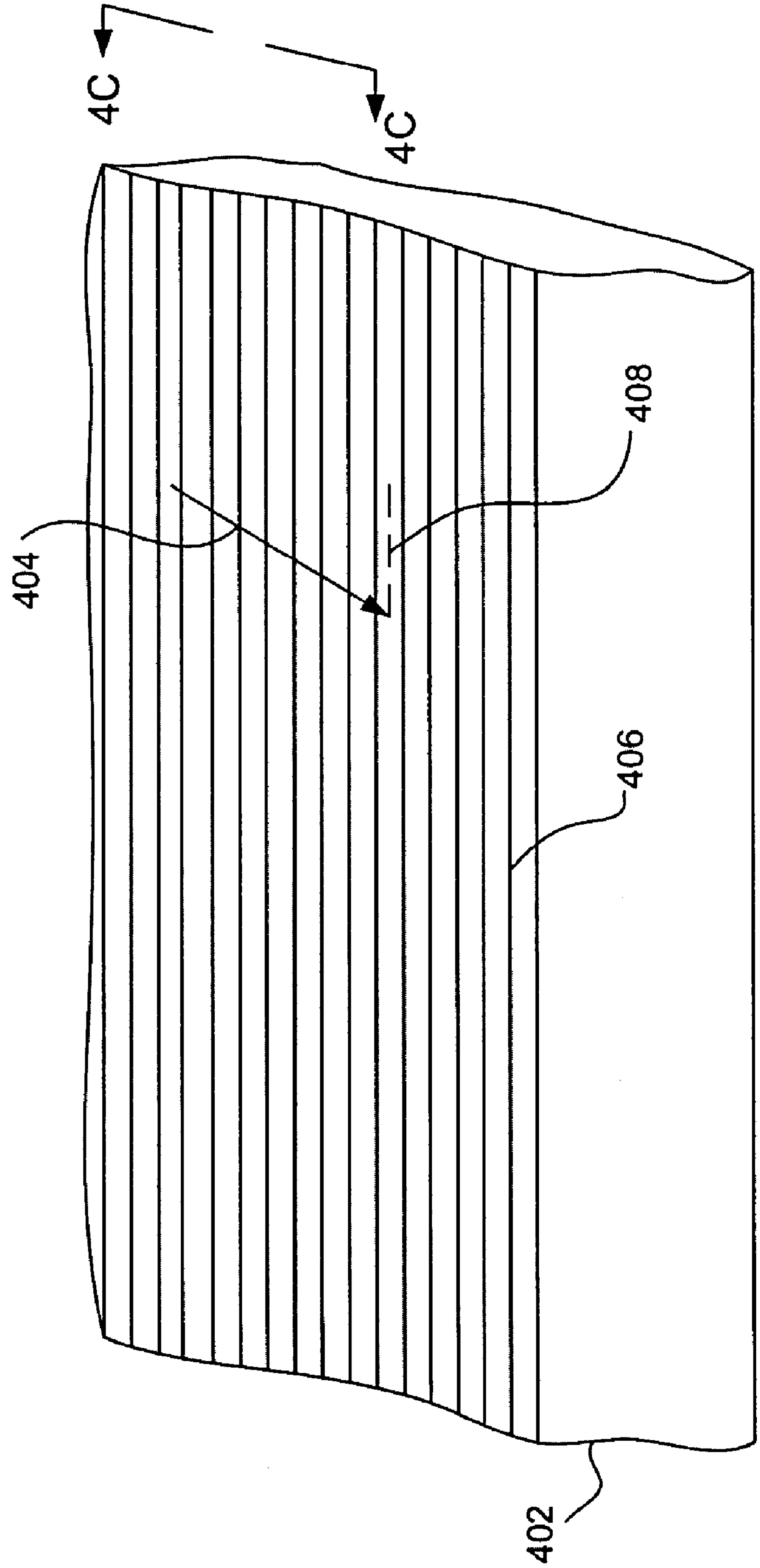


FIG. 4B

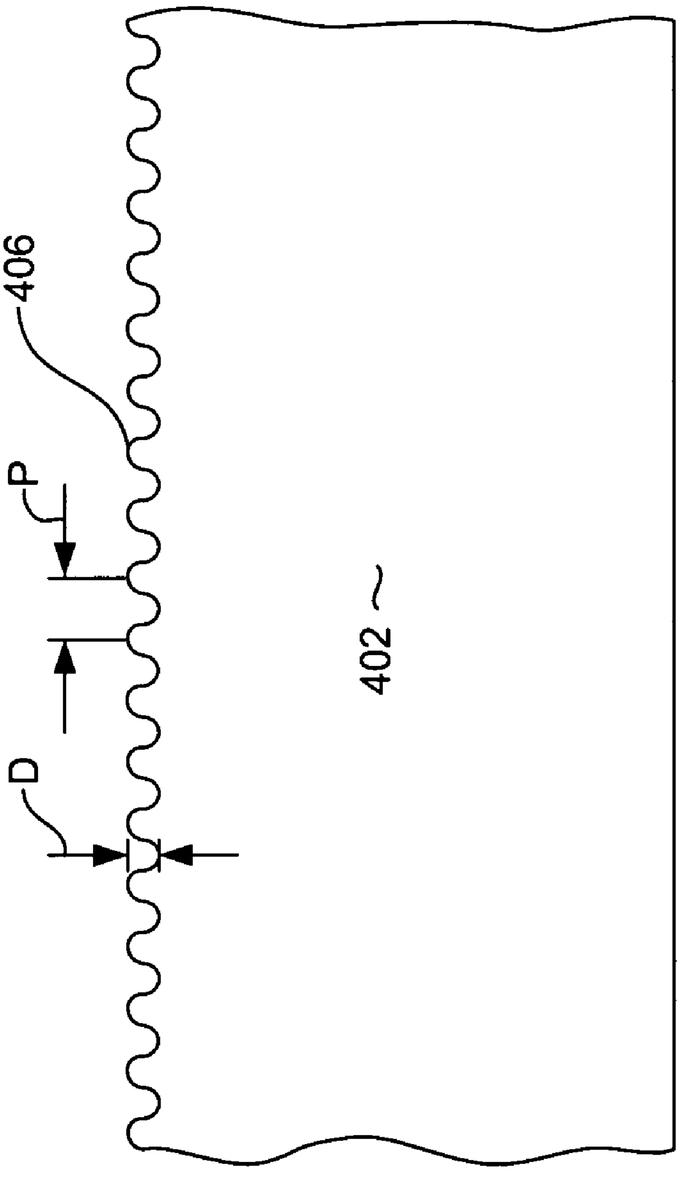


FIG. 4C

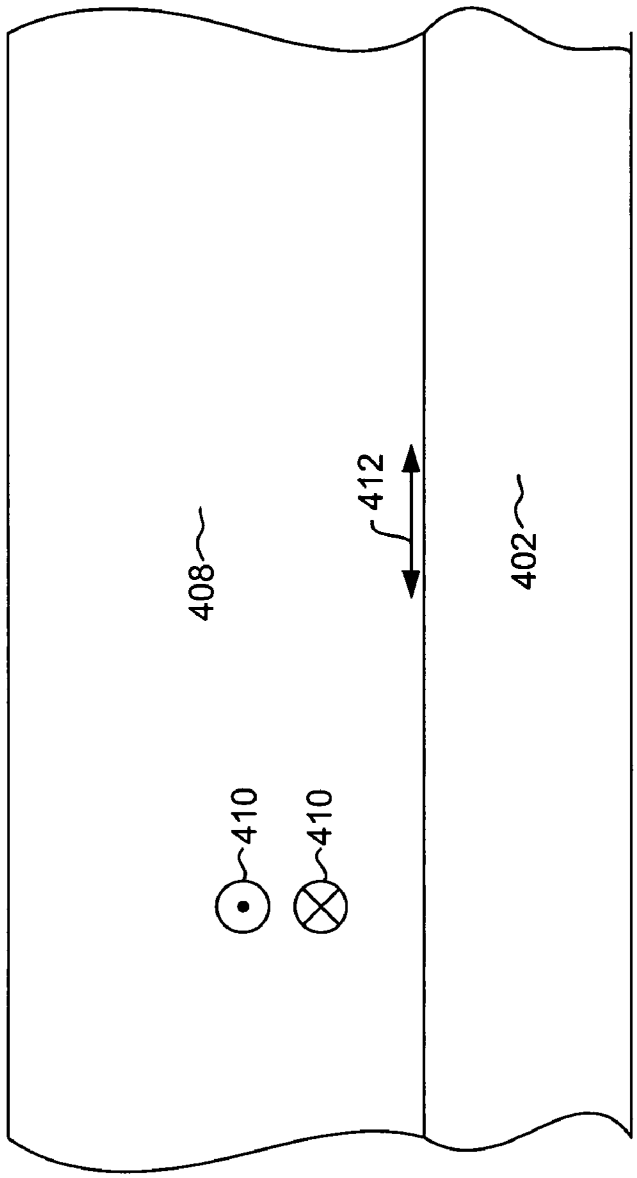


FIG. 4D

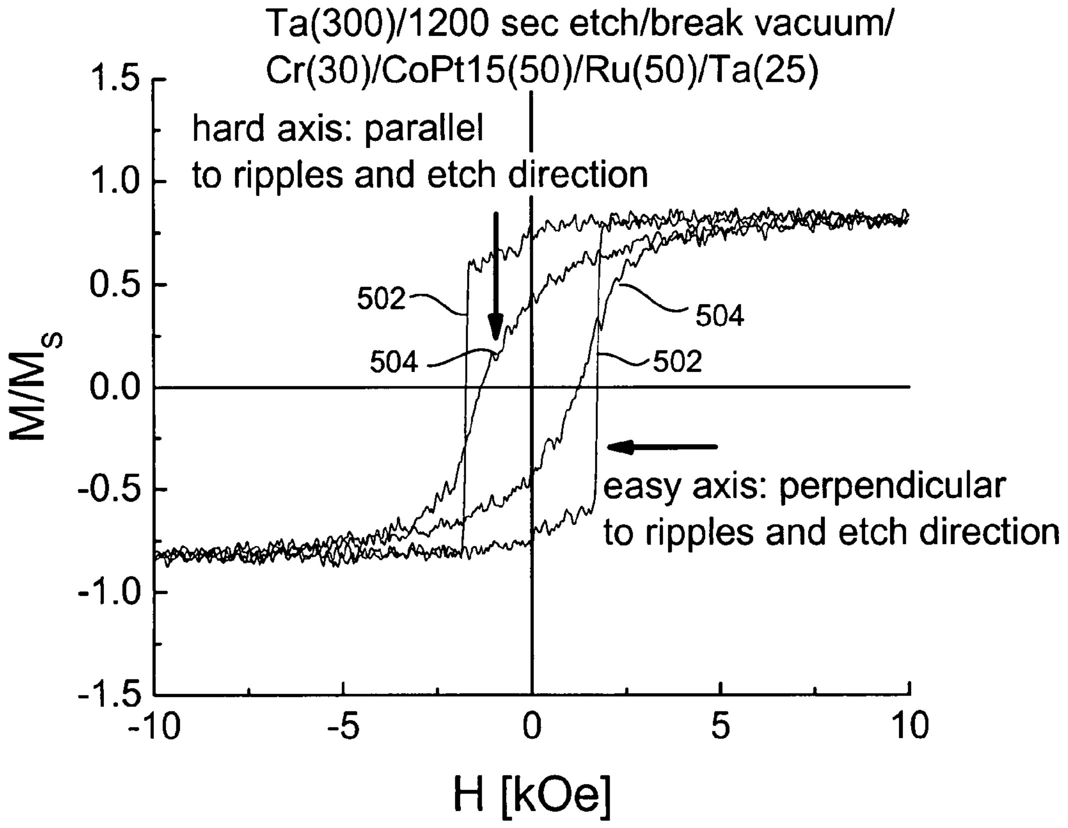

Ta(300)/1200 sec etch/break vacuum/
Cr(30)/CoPt15(50)/Ru(50)/Ta(25)
hard axis: parallel
to ripples and etch direction
easy axis: perpendicular
to ripples and etch direction
502
504
504
502
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
M/M$_s$
-10
-5
0
5
10
H [kOe]

FIG. 5

MAGNETIC READ SENSOR EMPLOYING OBLIQUE ETCHED UNDERLAYERS FOR INDUCING UNIAXIAL MAGNETIC ANISOTROPY IN HARD MAGNETIC BIAS LAYERS

The present invention is related to patent application Ser. No. 11/097,638 filed on Mar. 31, 2005 entitled MAGNETIC READ SENSOR EMPLOYING OBLIQUE ETCHED UNDERLAYERS FOR INDUCING UNIAXIAL MAGNETIC ANISOTROPY IN A HARD MAGNETIC IN-STACK BIAS LAYER having the same inventors as the present application.

The present invention is related to patent application Ser. No. 11/097,920 filed on Mar. 31, 2005 entitled MAGNETIC READ SENSOR EMPLOYING OBLIQUE ETCHED UNDERLAYERS FOR INDUCING UNIAXIAL MAGNETIC ANISOTROPY IN A HARD MAGNETIC PINNING LAYER having the same inventors as the present application

The present invention is related to patent application Ser. No. 11/097,543 filed on Mar. 31, 2005 entitled METHOD FOR MANUFACTURING A MAGNETIC READ SENSOR EMPLOYING OBLIQUE ETCHED UNDERLAYERS FOR INDUCING UNIAXIAL MAGNETIC ANISOTROPY IN A HARD MAGNETIC IN-STACK BIAS LAYER having the same inventors as the present application.

The present invention is related to patent application Ser. No. 11/097,546 filed on Mar. 31, 2005 entitled A METHOD FOR MANUFACTURING A MAGNETIC READ SENSOR EMPLOYING OBLIQUE ETCHED UNDERLAYERS FOR INDUCING UNIAXIAL MAGNETIC ANISOTROPY IN A HARD MAGNETIC PINNING LAYER having the same inventors as the present application.

The present invention is related to patent application Ser. No. 11/097,846 filed on Mar. 31, 2005 entitled A METHOD FOR MANUFACTURING A MAGNETIC READ SENSOR EMPLOYING OBLIQUE ETCHED UNDERLAYERS FOR INDUCING UNIAXIAL MAGNETIC ANISOTROPY IN HARD MAGNETIC BIAS LAYERS having the same inventors as the present application.

FIELD OF THE INVENTION

The present invention relates to magnetoresistive field sensors and more particularly to a sensor having hard magnetic bias layers with strong magnetic anisotropy formed on an obliquely etched underlayer.

BACKGROUND OF THE INVENTION

The heart of a computer's long term memory is an assembly that is referred to as a magnetic disk drive. The magnetic disk drive includes a rotating magnetic disk, write and read heads that are suspended by a suspension arm adjacent to a surface of the rotating magnetic disk and an actuator that swings the suspension arm to place the read and write heads over selected circular tracks on the rotating disk. The read and write heads are directly located on a slider that has an air bearing surface (ABS). The suspension arm biases the slider toward the surface of the disk and when the disk rotates, air adjacent to the surface of the disk moves along with the disk. The slider flies on this moving air at a very low elevation (fly height) over the surface of the disk. This fly height is on the order of nanometers. When the slider rides on the air bearing, the write and read heads are employed for writing magnetic transitions to and reading magnetic transitions from the rotating disk. The read and write heads are connected to processing circuitry that operates according to a computer program to implement the writing and reading functions.

The write head includes a coil layer embedded in first, second and third insulation layers (insulation stack), the insulation stack being sandwiched between first and second pole piece layers. A gap is formed between the first and second pole piece layers by a gap layer at an air bearing surface (ABS) of the write head and the pole piece layers are connected at a back gap. Current conducted to the coil layer induces a magnetic flux in the pole pieces which causes a magnetic field to fringe out at a write gap at the ABS for the purpose of writing the aforementioned magnetic impressions in tracks on the moving media, such as in circular tracks on the aforementioned rotating disk.

In recent read head designs a spin valve sensor, also referred to as a giant magnetoresistive (GMR) sensor, has been employed for sensing magnetic fields from the rotating magnetic disk. This sensor includes a nonmagnetic conductive layer, hereinafter referred to as a spacer layer, sandwiched between first and second ferromagnetic layers, hereinafter referred to as a pinned layer and a free layer, both of which can be made up by a plurality of layers. First and second leads are connected to the spin valve sensor for conducting a sense current therethrough. The magnetization of the pinned layer is pinned perpendicular to the air bearing surface (ABS) and is relatively insensitive to applied magnetic fields. The magnetic moment of the free layer is biased parallel to the ABS, but is free to rotate in response to external magnetic fields. The magnetization of the pinned layer is typically pinned by exchange coupling with an antiferromagnetic layer.

The thickness of the spacer layer is chosen to be less than the mean free path of conduction electrons through the sensor. With this arrangement, a portion of the conduction electrons is scattered by the interfaces of the spacer layer with each of the pinned and free layers. When the magnetizations of the pinned and free layers are parallel with respect to one another, scattering is minimal and when the magnetizations of the pinned and free layer are antiparallel, scattering is maximized. Changes in scattering alter the resistance of the spin valve sensor in proportion to cos $\ominus$, where $\ominus$ is the angle between the magnetizations of the pinned and free layers. Since $\ominus$ is near 90 degrees at zero field, the resistance of the spin valve sensor (for small rotations of the free layer from 90 degrees) changes proportionally to the magnitudes of the magnetic fields from the rotating disk. When a sense current is conducted through the spin valve sensor, resistance changes cause potential changes that are detected and processed as playback signals.

When a spin valve sensor employs a single pinned layer it is referred to as a simple spin valve. When a spin valve employs an antiparallel (AP) pinned layer it is referred to as an AP pinned spin valve. An AP pinned spin valve includes first and second magnetic layers separated by a thin nonmagnetic coupling layer such as Ru or Ir. The thickness of the coupling layer is chosen so as to antiparallel couple the magnetic moments of the ferromagnetic layers of the pinned layer. A spin valve is also known as a top or bottom spin valve depending upon whether the pinning layer is at the top (formed after the free layer) or at the bottom (before the free layer).

Magnetization of the pinned layer is usually fixed by exchange coupling one of the ferromagnetic layers (AP**1**) with a layer of antiferromagnetic material such as PtMn. While an antiferromagnetic (AFM) material such as PtMn does not in and of itself have a net magnetic moment, when exchange coupled with a magnetic material, it can strongly pin the magnetization of the ferromagnetic layer.

A CIP spin valve sensor is located between first and second nonmagnetic electrically insulating read gap layers and the first and second read gap layers are located between ferromagnetic first and second shield layers. In a merged magnetic head a single ferromagnetic layer functions as the second shield layer of the read head and as the first pole piece layer of the write head. In a piggyback head the second shield layer and the first pole piece layer are separate layers.

The ever increasing demand for greater data rate and recording density has lead a push to develop perpendicular to plane (CPP) sensors which are uniquely suited to use in such systems. CPP sensors include both CPP giant magneto-resistive (GMR) sensors, which use an electrically conductive spacer layer such as Cu as well as tunnel magneto-resistive (TMR) sensors, which use a thin, electrically insulating barrier layer like Al-oxide. The CPP GMR sensor operates based on spin-dependent bulk and interface scattering of the electrons while the TMR sensor operates based on the spin dependent tunneling of electrons through the barrier layer.

In order to stabilize the free layer in CIP GMR, CPP GMR, or CPP TMR sensors against fluctuations due to thermal agitation and to prevent it from breaking up into domains it needs to be biased. One form of biasing a sensor is by using a hard magnetic biasing layer, typically a $Co_{1-x}Pt_x$ or $Co_{1-x-y}Pt_xCr_y$ alloy (x being between 10 and 35 atomic % and y between 0 and 15 atomic %) deposited onto a suitable underlayer material on both sides and about the same level as the free layer. Typically the hard magnetic bias layers also comprise a seed layer of Cr or CrX (X=Mo, Ti, V) on which the magnetic $Co_{1-x}Pt_x$ or $Co_{1-x-y}Pt_xCr_y$ material is deposited to achieve crystalline texture and sufficiently high coercivity. An insulating gap separates the free and the hard biasing layers in CPP sensors to prevent electrical shunting. The hard magnetic bias layer has sufficiently high coercivity and remanence so that its remanent moment magnetostatically biases the free layer in a direction substantially parallel to the ABS. The total moment of the hard bias layer is typically several times the magnetic moment of the free layer. The actual moment value depends on the hard bias material, its shape and separation from the free layer.

One major problem with CoPt, CoPtCr, and other hard magnets in general is that they are magnetically isotropic in the plane and there is no pair ordering upon annealing which could establish a magnetic easy axis. Thus shape anisotropy needs to be employed to obtain an in-plane easy axis of the hard biasing layers in a direction substantially parallel to the ABS. As used herein substantially parallel means that the easy axis is closer to parallel than perpendicular to the ABS. Therefore the hard biasing layers are extended laterally in a direction parallel to the ABS, and parallel to the desired easy axis of the magnetic free layer. The ability of such shape induced anisotropy to produce a sufficiently strong in plane easy axis is, however, limited by design constraints. This is especially true in present and future generation extremely-small sensors.

Therefore, there is a strong felt need for a mechanism to generate a uniaxial magnetic anisotropy other than shape anisotropy to set the magnetic anisotropy of a hard magnetic layer such as CoPt or CoPtCr in a user defined direction independent of the shape of the sensor.

SUMMARY OF THE INVENTION

The present invention provides a hard bias layer structure having a magnetic easy axis (magnetic anisotropy) oriented in a specific direction substantially parallel with the ABS. The sensor includes a sensor stack and hard bias layers extending laterally from the sides of the sensor stack. The hard bias layer is deposited over an underlayer that has been ion beam etched at an angle with respect to the normal to the surface of the underlayer in order to form oriented ripples or facets in the surface of the underlayer.

The underlayer may comprise Pt, Ta, PtMn, Cr, Ru, W, Mo, Cu, their alloys, or other preferably crystalline materials. The hard bias layer deposited thereover may be, for example, CoPt, CoPtCr, typically on a seed layer of Cr or a Cr-alloy, or some other hard magnetic material on a suitable seed layer. The anisotropic roughness in form of oriented ripples formed by this ion etch may run along a direction substantially perpendicular to the ABS and induce a strong magnetic uniaxial anisotropy in the subsequently deposited hard magnetic biasing layers in a direction substantially parallel to the ABS.

The strong magnetic uniaxial anisotropy produced by the present invention ensures sufficient magnetic biasing of the free layer even at the extremely small sensor sizes of present and future generation sensors. The magnetic anisotropy of the hard bias layers also prevents loss of free layer biasing during high temperature events such as from a head-disk contact.

These and other advantages and features of the present invention will be apparent upon reading the following detailed description in conjunction with the Figures.

BRIEF DESCRIPTION OF THE DRAWINGS

For a fuller understanding of the nature and advantages of this invention, as well as the preferred mode of use, reference should be made to the following detailed description read in conjunction with the accompanying drawings which are not to scale.

FIG. **1** is a schematic illustration of a disk drive system in which the invention might be embodied;

FIG. **2**, is an ABS view of a CIP sensor according to a first embodiment of the invention;

FIG. **3** is an ABS view of a CPP sensor according to a second embodiment of the invention;

FIGS. **4**A through **4**D are cross sectional views illustrating a method of setting magnetic anisotropy in a magnetic layer according to the present invention; and

FIG. **5**. is a graph illustrating magnetic hysteresis loops of a $Cr(30)/Co_{82}Pt_{18}$ (50) film grown onto a 1200 seconds etched Ta underlayer measured perpendicular and parallel to the ion-beam direction.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The following description is of the best embodiments presently contemplated for carrying out this invention. This description is made for the purpose of illustrating the general principles of this invention and is not meant to limit the inventive concepts claimed herein.

Referring now to FIG. **1**, there is shown a disk drive **100** embodying this invention. As shown in FIG. **1**, at least one rotatable magnetic disk **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 annular patterns of concentric data tracks (not shown) on the magnetic disk **112**.

At least one slider **113** is positioned near the magnetic disk **112**, each slider **113** supporting one or more magnetic head assemblies **121**. As the magnetic disk rotates, slider **113** moves radially in and out over the disk surface **122** so that the magnetic head assembly **121** may access different tracks of the magnetic disk 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 slider **113** against the disk 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 comprises 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 controller **129**.

During operation of the disk storage system, the rotation of the magnetic disk **112** generates an air bearing between the slider **113** and the disk surface **122** which exerts an upward force or lift on the slider. The air bearing thus counter-balances the slight spring force of suspension **115** and supports slider **113** off and slightly above the disk surface by a small, substantially constant spacing during normal operation.

The various components of the disk storage system 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 disk **112**. Write and read signals are communicated to and from write and read heads **121** by way of recording channel **125**.

With reference now to FIG. **2**, a CIP GMR sensor **200** having hard bias layers manufactured according to the present invention is described. The sensor **200** includes a sensor stack **202** sandwiched between first and second non-magnetic, electrically insulating gap layers **204**, **206**. The first and second hard bias layers **208**, **210** extend laterally from the sides of the sensor stack **202**. The hard bias layers are deposited over underlayers **212**, **214** which will be described in greater detail herein below. First and second leads **216**, **218** are deposited over the hard bias layers **208**, **210**, and may be constructed of for example Au, Rh or some other electrically conductive material.

With continued reference to FIG. **2**, the sensor stack **202** includes a magnetic free layer **220**, a magnetic pinned layer structure **222** and a spacer layer **224** sandwiched between the free and pinned layers **220**, **222**. The free layer **220** has a magnetic moment **221** that is biased in a direction parallel with a medium facing surface, which may be an air bearing surface or a contact bearing surface. Although moment **221** is biased parallel with the medium facing surface, it is free to rotate in response to a magnetic field. The pinned layer may be of various configurations, such as simple, AP coupled, AFM pinned or self pinned. The free layer **220** can be constructed of one or more layers of for example NiFe, Co, CoFe or other sufficiently soft magnetic material, preferably with a layer of Co or CoFe adjacent to the spacer layer **224**. The spacer layer **224** can be constructed of a non-magnetic, electrically conductive material such as Cu.

The pinned layer **222** is preferably an AP coupled pinned layer having first and second magnetic layers AP**1** **226** and AP**2** **228** which are antiparallel coupled across an AP coupling layer **230**. The AP**1** and AP**2** layers can be for example CoFe or some other suitable magnetic material. The coupling layer **230** can be constructed of, for example, Ru or Ir and is constructed of a thickness chosen to strongly antiparallel couple the magnetic moments **234** and **236** of the AP**1** and AP**2** layers, respectively. The coupling layer can be for example 2-10 Angstroms thick or about 8 Angstroms thick. The AP**1** layer **226** is exchange coupled with a layer of antiferromagnetic material (AFM layer **232**) which strongly pins the magnetic moment **234** of the AP**1** layer **226** in a desired direction perpendicular to the medium facing surface and due to AP coupling of the AP**1** and AP**2** layers **226** and **228** pins the moment **236** of the AP**2** layer **228** in a desired direction perpendicular to the medium facing surface, but antiparallel with the moment **234** of the AP**1** layer **226**.

A seed layer **238** may be provided at the bottom of the sensor stack **202** to promote a desired grain structure on the subsequently deposited sensor layers. In addition, a capping layer **240**, such as Ta, may be provided to protect the layers of the sensor stack **202** from damage during manufacture.

With reference still to FIG. **2**, the hard magnetic bias layers **208**, **210** are constructed of a magnetic material having a high coercivity of 1.5 kOe or higher, preferably $Co_{1-x}Pt_x$ or $Co_{1-x-y}Pt_xCr_y$ (x being between 10 and 35 atomic % and y between 0 and 15 atomic %). Typically the hard magnetic bias layers also comprise a seed layer of Cr or CrX (X=Mo, Ti, V) on which the magnetic $Co_{1-x}Pt_x$ or $Co_{1-x-y}Pt_xCr_y$ material is deposited to achieve crystalline texture and sufficiently high coercivity. The magnetic hard bias layers have magnetic moments that are set substantially parallel to the medium facing surface in order to bias the moment **221** of the free layer in a desired direction substantially parallel with the medium facing surface. The bias layers **208**, **210** are formed on underlayers **212**, **214** which can be for example Pt, Ta, PtMn, Cr, Ru, W, Mo, Cu, their alloys, or other suitable, preferably crystalline material and have been treated as described with reference to FIGS. **4**A-4D in order to create anisotropic roughness on the surface of the underlayers **212**, **214** and to induce a magnetic anisotropy axis **242** in the bias layers **208** and **210** in a direction substantially parallel with the medium facing surface. This means that the underlayers **212**, **214** have been ion beam etched prior to deposition of the hard magnetic bias layers **208**, **210** at an angle and direction that must be chosen such that the resulting magnetic easy axis of the hard magnetic bias layers **208**, **210** is substantially parallel to the medium facing surface.

The underlayers **212**, **214** (which may have a thickness of 30-300 Angstroms after etching) exhibit anisotropic roughness for example in form of oriented ripples or facets in their upper interfaces that run along a direction oriented substantially perpendicular to the medium facing surface (into and out of the plane of the page in FIG. **2**). The upper surface of the underlayer may have been oxidized prior to deposition of the hard magnetic bias layer.

FIG. **5** shows magnetic hysteresis loops of hard bias layer **208**, **210** formed over an underlayer **212**, **214** treated as described above. The lines **502** show the hysteresis loop in response to a magnetic field parallel with the easy axis of the hard bias layer **208**, **210**. The lines **504** show the hysteresis loops in response to a magnetic field that is perpendicular to the easy axis of the hard bias layers **208**, **210**. The strong anisotropy **242** of the hard magnetic bias layers **208**, **210** greatly facilitates effective biasing of the free layer **220**. As sensors become smaller, effective stable biasing becomes increasingly difficult. The strong anisotropy **242** provided by the present invention, therefore, greatly facilitates stable free layer biasing in a very small magnetoresistive sensor.

With reference to FIG. **3**, the present invention can also be practiced in a CPP sensor, such as a CPP GMR or CPP TMR sensor, having a sensor stack **302** comprising a pinned layer structure **304**, and a free layer **306**. For a CPP GMR sensor the free and pinned layers **304**, **306** are separated by a non-magnetic, electrically conductive spacer layer **312**, which may be, for example, Cu. For a CPP TMR sensor the free and pinned layers **304**, **306** are separated by a non-magnetic, electrically insulating barrier layer **312**, which may be, for example, Al-oxide. A capping layer **314**, such as Ta, may also be provided at the top of the sensor stack **302** to protect the sensor layers from damage during manufacture.

With continued reference to FIG. **3**, the sensor stack is sandwiched between first and second electrically conductive, magnetic shields **316**, **318** which may be constructed of, for example NiFe, and serve as first and second electrical leads for providing a sense current to the sensor stack **302**. Hard magnetic bias layers **320**, **322** are provided for biasing the magnetic moment **324** of the free layer **306** in a direction substantially parallel with the medium facing surface. First and second insulation layers **326**, **328** are provided to prevent current shunting between the shields through the hard bias layers **320**, **322**.

The free layer **306** may be constructed of one or more layers of for example NiFe, Co, CoFe, or other sufficiently soft magnetic material, preferably with a layer of Co or CoFe adjacent to the spacer layer **312**. The pinned layer structure **304** may be a simple, single layer pinned layer, but is more preferably an AP pinned structure having first and second magnetic layers AP1 **330**, AP2 **332** separated from one another by an antiparallel coupling layer (AP coupling layer) **334**. The AP1 and AP2 layers **330**, **332** can be constructed of, for example, CoFe and the AP coupling layer **334** can be Ru or Ir.

As with the previously described embodiment, the first magnetic layer **330** can be exchange coupled with a layer of antiferromagnetic material **308** to pin the magnetizations **338**, **339** of the magnetic layers **330**, **332**. A seed layer **310** may be provided at the bottom of the sensor stack **302**.

With reference still to FIG. **3**, the hard magnetic bias layers **320**, **322** are constructed of a magnetic material having a high coercivity of 1.5 kOe or higher, preferably $Co_{1-x}Pt_x$ or $Co_{1-x-y}Pt_xCr_y$ (x being between 10 and 35 atomic % and y between 0 and 15 atomic %). Typically the hard magnetic bias layers also comprise a seed layer of Cr or CrX (X=Mo, Ti, V) on which the magnetic $Co_{1-x}Pt_x$ or $Co_{1-x-y}Pt_xCr_y$ material is deposited to achieve crystalline texture and sufficiently high coercivity. The hard bias layers have magnetic moments that are set substantially parallel to the medium facing surface in order to bias the moment **324** of the free layer in a desired direction substantially parallel with the medium facing surface. The hard magnetic bias layers **320**, **322** are formed on underlayers **340**, **342** which can be for example Pt, Ta, PtMn, Cr, Ru, W, Mo, Cu, their alloys or another suitable, preferably crystalline material. The underlayers **340**, **342** have been treated as described with reference to FIGS. **4A-4D** in order to create anisotropic roughness on the surface of the underlayers **340**, **342** and to induce a magnetic anisotropy axis **350** in the bias layers **320** and **322** in a direction substantially parallel with the medium facing surface. This means that the underlayers **340**, **342** have been ion beam etched prior to deposition of the hard magnetic bias layers **320**, **322** at an angle and direction that must be chosen such that the resulting magnetic easy axis of the hard magnetic bias layers **320**, **322** is substantially parallel to the medium facing surface.

The underlayers **340**, **342** (which may have a thickness of 30-300 Angstroms after etching) exhibit anisotropic roughness for example in form of oriented ripples or facets in their upper interface that run along a direction oriented substantially perpendicular to the medium facing surface (into and out of the plane of the page in FIG. **3**).

The strong anisotropy **350** of the bias layers **320**, **322** greatly facilitates effective biasing of the free layer **306**. As sensors become smaller, effective stable biasing becomes increasingly difficult. The strong anisotropy **350** provided by the present invention, therefore, promotes stable free layer biasing in a very small magnetoresistive sensor.

With reference to FIGS. **4**A through **4**D, The underlayers **212**, **214** (FIG. **2**) and **340**, **342** (FIG. **3**) are constructed by depositing a material **402**, which could be for example Pt, Ta, PtMn, Cr, Ru, W, Mo, Cu, their alloys, or some other suitable, preferably crystalline, material. The underlayer material **402** can be for example 30 to 300 Angstroms or about 100 Angstroms thick after ion beam etching. An ion beam etch **404** is then performed at an angle Θ with respect to a normal to the surface of the underlayer **402**. The angled ion etch induces anisotropic roughness for example in form of oriented ripples or facets **406** that run in a direction substantially parallel to the in plane projection **408** of the ion beam onto the surface of the layer **402**. The typical or average pitch P of the ripples **406** is between 10-200 nm, their average depth D is between 0.5 to 5 nm or about 1 nm.

After the angled ion etch **404** has been performed sufficiently to form the desired ripples or facets **406**, a layer of hard magnetic material **408** (FIG. **4**D) is deposited. The hard magnetic material **408** can be for example CoPt or CoPtCr can include multiple layers, such as a seed layer of Cr or CrX (X=Mo, Ti, V) and a layer of CoPt or CoPtCr. The magnetic easy axis **410** of the applied hard magnetic material **406** will be substantially perpendicular to the direction **412** of the ripples and substantially perpendicular to the in plane projection **406** (FIG. **4**B) of the angled ion etch onto the surface of the under layer **402**. If another suitable hard magnetic material is used instead of CoPt or CoPtCr, the magnetic easy axis may be either substantially parallel or substantially perpendicular to the direction **412** of the ripples. The ion etch direction must be chosen such that the resulting magnetic easy axis of the hard magnetic bias layers is substantially parallel to the medium facing surface.

The angled ion etch **404** is preferably performed at an angle of between 20 and 80 degrees and is more preferably performed at an angle of between 35 and 65 degrees with respect to the normal to the surface of the underlayer **402**. The exact voltage, current, and angle conditions depend on the type and characteristics of the ion source in use.

In one demonstration of the above described treatment method, about 300 Angstroms of Ta were deposited and etched under an angle of about 45 degrees from normal for 1200 seconds at an ion source voltage of 100 Volts and a flux of 1 Ampere. The etch rate was about 5-7 Angstroms per minute. The Ta samples were taken out of vacuum and reintroduced into another deposition system. Thus some oxide layer formed on the top of the Ta. Finally a seed layer of about 30 Angstroms of Cr, about 50 Angstroms of $Co_{82}Pt_{18}$ hard magnetic bias material, and about 50 Angstroms of Ru, and about 25 Angstroms of Ta cap material were deposited onto the treated underlayer. Magnetization measurements shown in FIG. **5** demonstrate that a uniaxial anisotropy is introduced by the ion beam etch. The easy axis is perpendicular to the in-plane projection of the ion beam during etching. The structural origin was investigated by X-ray diffraction. The reflectivity rocking curves of an etched Ta substrate taken with the projection of the X-rays and the ion beam parallel and perpendicular to each other exhibit an enhancement of the diffusive background in the direction perpendicular to the ion beam. This is a clear indication of the change in substrate morphology with anisotropic roughness for example in form of oriented ripples or facets running along the direction of the ion beam. The $Co_{82}Pt_{18}$ easy axis is perpendicular to axis of the ripples or facets. Underlayers with various crystalline structures including Ta (body centered tetragonal), Cr (body centered cubic), PtMn (body centered tetragonal), Cu (face centered cubic), and Ru (hexagonal closed packed) have been ion beam etched in a fashion similar to what is described above and a Cr(35)/$CoPt_{18}$(50) bilayer was deposited ontop. Magnetic measurements revealed a $CoPt_{18}$ easy axis perpendicular to the ion beam direction showing that the effect is independent of the type of crystalline structure.

While various embodiments have been described above, it should be understood that they have been presented by way of example only, and not limitation. Other embodiments falling within the scope of the invention may also become apparent to those skilled in the art. Thus, the breadth and scope of the invention should not be limited by any of the above-described exemplary embodiments, but should be defined only in accordance with the following claims and their equivalents.

What is claimed is:

1. A magnetoresistive sensor having an air bearing surface, comprising:

a sensor stack including a magnetic free layer, a magnetic pinned layer, and a non-magnetic layer sandwiched between the free and pinned layers;

an underlayer extending laterally from the sensor stack, the underlayer having a surface that has an anisotropic roughness;

a hard magnetic bias layer, formed over the underlayer and extending laterally from the sensor stack.

2. A magnetoresistive sensor as in claim **1** wherein the hard magnetic bias layer has a magnetic anisotropy oriented substantially parallel to the air bearing surface.

3. A magnetoresistive sensor as in claim **1** wherein the anisotropic roughness comprises ripples or facets.

4. A magnetoresistive sensor as in claim **1** wherein the anisotropic roughness comprises ripples or facets that extend along a direction substantially perpendicular to the air bearing surface.

5. A magnetoresistive sensor as in claim **1** wherein the underlayer comprises a material having a crystalline structure.

6. A magnetoresistive sensor as in claim **1** wherein the underlayer comprises a material having body centered cubic or body centered tetragonal crystal structure.

7. A magnetoresistive sensor as in claim **1** wherein the underlayer comprises a material having face centered cubic or face centered tetragonal crystal structure.

8. A magnetoresistive sensor as in claim **1** wherein the underlayer comprises a material having hexagonally closed packed crystal structure.

9. A magnetoresistive sensor as in claim **1** wherein the underlayer comprises Pt, Ta, PtMn, Cr, Ru, W, Mo, Cu, or their alloys.

10. A magnetoresistive sensor as in claim **1** wherein the surface of the underlayer is oxidized.

11. A magnetoresistive sensor as in claim **1** wherein the upper surface of the underlayer exhibits anisotropic roughness in the form of ripples having an average pitch of 10-200 nm.

12. A magnetoresistive sensor as in claim **1** wherein the upper surface of the underlayer exhibits an anisotropic roughness in form of ripples having an average depth of 0.5-5 nm.

13. A magnetoresistive sensor as in claim **1** wherein the underlayer has a thickness of 30-300 Angstroms after ion beam etching.

14. A magnetoresistive sensor as in claim **1** wherein the hard magnetic bias layer comprises an alloy of Co and Pt.

15. A magnetoresistive sensor as in claim **1** wherein a crystalline seed layer is disposed between the underlayer and the hard magnetic bias layer, and wherein the hard magnetic bias layer comprises an alloy of Co and Pt.

16. A magnetoresistive sensor as in claim **1** wherein a seed layer of Cr or CrX (X=Mo, Ti, V) is disposed between the underlayer and the hard magnetic bias layer, and wherein the hard magnetic bias layer comprises an alloy of Co and Pt.

17. A magnetoresistive sensor as in claim **1** wherein the hard magnetic bias layer comprises an alloy of $CoPt_xCr_y$, x being between 10 and 35 atomic percent and y being between 0 and 15 atomic percent.

18. A magnetoresistive sensor as in claim **1** wherein a crystalline seed layer is disposed between the underlayer and the hard magnetic bias layer and wherein the hard magnetic bias layer comprises $CoPt_xCr_y$, x being between 10 and 35 atomic percent and y being between 0 and 15 atomic percent.

19. A magnetoresistive sensor as in claim **1** wherein a seed layer of Cr or CrX (X=Mo, Ti, V) is disposed between the underlayer and the hard magnetic bias layer and wherein the hard magnetic bias layer comprises $CoPt_xCr_y$, x being between 10 and 35 atomic percent and y being between 0 and 15 atomic percent.

20. A magnetoresistive sensor as in claim **1** wherein the hard bias layer comprises an alloy of Co and the wherein the underlayer comprises a material having a crystalline structure.

21. A magnetoresistive sensor as in claim **1** wherein the hard bias layer comprises an alloy of $CoPt_xCr_y$, x being between 10 and 35 atomic percent and y being between 0 and 15 atomic percent and wherein the underlayer comprises a material having crystalline structure.

22. A magnetoresistive sensor as in claim **1** wherein the hard bias layer comprises an alloy of $CoPt_xCr_y$, x being between 10 and 35 atomic percent and y being between 0 and 15 atomic percent and wherein the underlayer comprises a material selected from the group consisting of Pt, Ta, PtMn, Cr, Ru, W, Mo, Cu, or their alloys.

23. A magnetoresistive sensor as in claim **1**, wherein the sensor is a current in plane GMR sensor.

24. A magnetoresistive sensor as in claim **1** wherein the sensor is a current perpendicular to plane GMR sensor.

25. A magnetoresistive sensor as in claim **1** wherein the sensor is a tunnel valve.

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