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# A MAGNETORESISTIVE SENSOR & METHOD OF MAKING THE SAME

The present invention relates to a magnetoresistive sensor and method of making the same. In particular, but not exclusively, the present invention relates to magnetic recording disk drives and more particularly to magnetoresistive heads therefor.

Magnetoresistive (MR) heads of the canted-current type derived from a head type known as a barber pole MR head, exhibit a skewed read sensitivity function primarily due to the variation in distance of the contact edges from the input surface (the sensor's output is proportional to this distance), particularly the sharp corners between the contacts and the MR element. The problem is illustrated in Figure 1, where the MR element 10 extends left to right in the figure and the contacts 12 are canted across the sensor at approximately 45 degrees, creating a sense region where current I primarily flows (perpendicular to the contact edges) across the sense region at approximately 45 degrees relative to the MR element's magnetization vector M. However, in the cross-hatched triangular region 16, current flows at a shallower angle more parallel with the MR element's magnetization vector than it is in the center of the sense region. Because of magnetization rotation and the presence of sense current in this region, detection is still possible. As a result, the read sensitivity extends farther to the left than to the right thus producing a skewed read sensitivity function.

The read sensitivity function we discuss herein is the sensitivity of the sensor vs. location across the sensor for a microtrack of recorded information less than one micrometer in width. The read sensitivity function for the MR sensor illustrated in Figure 1 is shown in Figure 2 as line 18. Due to the presence of the current vector I and the MR element's

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magnetization vector **M** in the cross-hatched region 16, the read sensitivity function 18 is asymmetric and exhibits a substantially large tail 20 extending to the left in the figure.

There are two problems when using such an asymmetric MR sensor in an application such as a magnetic disk drive in which the MR sensor may be required to read both data and servo information from very narrow tracks on a magnetic disk surface. The first problem is noise and cross-talk because of the excessively long tail on the read sensitivity function. The second is the use of the sensor to read analog servo data. Due to the asymmetrical nature of the read sensitivity function, the response to servo data from left and right are not equivalent - thus requiring special compensation to make this application practical.

One proposed solution to this problem is to deactivate the undesired region 16 by poisoning the MR element (Permalloy) by diffusion or ion implantation. Applicant's solution is to substitute for the MR element (Permalloy) in the undesired region another material where the change in resistivity vs. magnetization is essentially zero.

According to the present invention, there is provided a magnetoresistive sensor comprising:

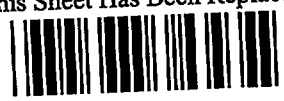
a thin film magnetoresistive element having at least one end having unsaturated dipoles in the absence of a stabilising magnetic field, and a magnetisation vector $M_1$ and at least one bias edge not parallel with the magnetisation vector, the magnetoresistive element having a thickness $t_1$ and the magnetisation vector being disposed at an angle $theta_1$ to the bias edge;

contact means for supplying a sense current to the magnetoresistive element;

a thin film permanent magnetic layer aligned in a substantially adjacent and co-planar relationship with the bias edge of the magnetoresistive element, the permanent magnetic layer

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having a thickness $t_2$ and a magnetisation vector $M_2$ being disposed at an angle $theta_2$ to the bias edge;

a gap being provided between the magnetoresistive element and the magnetic layer; and characterised in that

$$M_1 * t_1 * \sin(theta_1) = M_2 * t_2 * \sin(theta_2).$$

Embodiments of the present invention will now be described with reference to the accompanying drawings, of which:

Figure 1 is a plan view diagram of the essential layers of a conventional, canted-current MR sensor.

Figure 2 shows the read sensitivity function for the sensor of Figure 1.

Figure 3 is a diagram of a Magnetoresistive sensor according to a preferred embodiment of the present invention.

Figure 4 shows the read sensitivity function of the sensor of Figure 3.

Figure 5a & 5b are cross sections along 5a-5a' and 5b-5b' of Figure 3.

Figure 6a is a diagram of an alternative magnetoresistive sensor having an optional insulator layer.

Figure 6b is a cross section along 6b-b' of Figure 6a.

Figures 7a-d illustrate a preferred method for forming the alternative embodiment of Figures 6a and 6b.

Figure 8 is a diagram of an alternative embodiment having a triangularly shaped MR element which permits the use of less bias current.

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Figure 9 is a diagram of a further alternative embodiment in which both the sensor and contacts are constructed so as to provide a magnetoresistive sensor with a lip designed to make the read sensitivity invariant with lapping.

Figure 10 is a variation on the preferred embodiment in which the inefficient portions of the MR element are removed.

Figure 11 is a diagram of an alternative construction of an MR element in which the at-rest magnetization vector of the MR element is rotated and wherein the rotated sensor is also provided with a lip separately stabilized.

Figure 12 is a diagram of an generalized configuration of the lip stabilization for the sensor of Figure 11 that may be applied to any design.

Figure 13 is a diagram of an embodiment providing for a rotated, at-rest magnetization, squared-off contacts, and a lip, in which the read sensitivity function is relatively tolerant to lapping.

Figure 14 is a diagram of a preferred lip structure with an expanded rear region to provide flux for a wider sensor than that determined by the lip width at the air bearing surface.

Figure 15 is a diagram of an alternative embodiment illustrating a hybrid contact structure which yields improved read sensitivity symmetry.

Figure 3 is a diagram of a preferred embodiment of the present invention. The figure shows a canted-current configured magnetoresistive sensor in which the current contacts 12 are substantially canted across the MR element while the magnetization vector **M** of the element is aligned along the width of the sensor. In the figure, the MR element is defined as a substantially square element 10, centered between the gap in current contacts 12. The ends of

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the MR element are stabilized by permanent magnetic layers 22 and 24. The permanent magnetic layers 22 and 24 abut the ends of the square MR element, but are separated therefrom by small gaps 26. The sense current contacts 12 overlay these layers and have edges which cross the MR element at approximately 45° to M, with the distance between the contacts chosen such that the points 28 and 28' where the respective contacts 12 cross the gaps 26 lie close to the horizontal center of the MR element.

In this configuration, the sense current I flows between the contacts 12 substantially only in a central region defined between these two intersections, 28 and 28', and does not flow through the undesired region 16 due to gaps 26. The elongated tail in the read sensitivity function on the left is therefore eliminated.

Because the effective sense current is confined as above described, the read sensitivity function is substantially symmetrical and "squared up" as illustrated in Figure 4. The output from region 16 is eliminated, cutting off the troublesome tail 20 in Figure 2.

Turning to Figures 5a and 5b, which are partial cross-sections along 5a-5a' and 5b-5b' in Figure 3, the permanent magnetic layers 22 and 24 are shown in combination with Magnetoresistive element or layer 10 and metallic current contacts 12. Due to the requirement to control the magnetic boundary conditions between the permanent layers 22 and 24 and the magnetoresistive layer 10, which will be discussed subsequently, the magnetoresistive layer 10 will typically be substantially the same thickness as the permanent magnetic layer 22. Conventionally, the magnetoresistive layer will be on the order of 30nm (300 Å) thick. As illustrated in the figure, the preferred permanent magnetic layers 22 and 24 will also be on the order of 30nm (300 Å) thick. As well known in the art, the metallic current contacts 12 can be

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made substantially thicker than either the permanent magnetic or Magnetoresistivelayers. In the figure, the contacts 12 are preferably on the order of 100nm (1000 Å) thick.

While the preferred embodiment has a small gap between the permanent magnet and the magnetoresistive layer, this is not necessary if the permanent magnet layer's resistivity is chosen such that it is much higher than that of the MR layer. With such a configuration, the sensor may be formed using methods such as disclosed in U.S. Patent 5,079,035, which is hereby incorporated by reference as if fully set forth herein. See also U.S. 5,018,037. A preferred method for forming a gap between the layers will be discussed in relation to figures 7a-d.

In the preferred embodiment, the magnetoresistive element is preferably composed of the alloy $Ni_{82}$ $Fe_{18}$ (Permalloy). The permanent magnetic layers are preferably one of the following (or similar) alloys: $Co_{78}$ $Pt_{22}$; $Co_{78}$ $Cr_8$ $Pt_{14}$; or $Co_{80}$ $Sm_{20}$. The contacts layers are preferably composed of a trilayer of Mo-Au-Mo, but many other conducting metals may be used.

A single-domain MR element having edges at which magnetization M is directed other than parallel to the edge will exhibit a net external magnetic field at the edges which may cause the element to become unstable. These edge regions can then "fracture" into multiple domains with the net internal field of one domain cancelling the net internal field of adjacent domains.

In order to maintain such an element in a single domain state, various techniques may be employed, one of which is to apply an external magnetic field in order to keep magnetic dipoles of the crystalline alloy aligned in the preferred direction. This has been know in the

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past as "longitudinal biasing." See e.g., U.S. patent 4,967,298 for a discussion of the single domain problem and its previously known solutions.

In the past, the exact amount of external magnetic field necessary to keep an MR element in a single domain state has not been fully explored. See for example the discussion in the aforementioned '037 patent at column 2, ll. 3-4.

We believe that the proper amount of permanent magnetic layer is that sufficient to produce the same magnetic flux as that of the saturated MR element layer at the boundary of the MR element. Exceeding this amount of flux - although it also serves to keep the MR element in a single domain state - will act to decrease the sensitivity of the MR element to (transverse) input flux.

Because the length of contact (into the figure) between the layers at their abutting end regions are equal, the flux matching requirement can be expressed as

$$M_r(PM) * t(PM) = M_r(MR) * t(MR),$$

where $M_r$ is the at-rest magnetization, "PM" is an abbreviation for "permanent magnet," and "t" is the thickness of the respective layers. Because the $M_r$ of typical permanent magnetic materials to be used in the present application are approximately equal to that of the MR materials, the permanent magnetic layer will be approximately as thick as the MR layer. For Permalloy which typically has a square loop, $M_r$ is close to the saturation value $M_s$.

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With the permanent magnetic layer thickness thus chosen, not only are demagnetizing fields in the MR element layer controlled, but there is little or no "excess" longitudinal magnetic field in the central active region of the MR element which would interfere with sensor performance.

Returning to Figure 3 for a moment, it was above noted that in some configurations, current could flow in the undesired region 16. This current will not affect the read sensitivity function because the material located in the undesired region does not exhibit a magnetoresistive response. However, any current flowing in this area detracts from the current that could flow in the sense region and is therefore undesirable from the efficiency standpoint.

A further improvement to enhance the electrical isolation of the permanent magnet layers is illustrated in Figures 6a and 6b. In these figures, a small amount of electrically insulating material 23,25 has been interposed between the permanent magnetic layer 22, 24 and the MR element 10 to form a "spacer" 50 which is preferably formed of an oxide such as $Al_2O_3$.

This spacer 50 effectively electrically isolates the MR layer and the current carrying contacts from the permanent magnetic layer while also permitting the magnetic flux coupling required to hold the MR layer in a single-domain state. Use of the spacer will substantially confine all sense current to only those portions of the MR element for which the read sensitivity function is nearly symmetrical.

The structure shown in Figures 6a and 6b may be formed by using a process such as illustrated in Figures 7a-d.

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Referring first the Figure 7a, the conventional MR head is formed upon a substrate comprising a basecoat 60, a soft magnetic shield, 62, and a half-gap oxide layer 64, conventionally composed of aluminum oxide. The MR element 10 of the present invention is deposited and patterned upon this oxide layer 64 by using a special bi-layer lift off resist which has an upper section 67 broader than the lower section 66. (A single layer resist may also be used in an alternative approach.) In the inventive process, the MR element is over etched using a chemical etchant such that the resulting MR element has a width slightly less than the overlying resist structure.

Referring to Figure 7b, the permanent magnetic layers are now sputter deposited using these resist layers as a mask. This results in a structure, such as illustrated in Figure 7b, where the permanent magnetic layers 22 and 24 are separated from the MR element 10 by small gaps 26.

After the deposition of the permanent magnetic layers, the resist is removed by a lift off process. Thereafter, an electrical insulator layer 27 is deposited over the whole sensor. See Figure 7c. This electrical insulator layer could be aluminum oxide, such as $AL_2O_3$. Next another layer 68 of resist is deposited over the insulator and patterned to expose 70 most of the MR layer 10, leaving small areas along the edge of the MR element covered by the resist. Using this resist mask 68, the insulator 27 is removed from over the MR sensor with an appropriate process such as selective chemical etching or ion milling to thereby expose the MR layer in this central gap region 70.

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Thereafter, the resist 68 is striped and the contacts 12 and 12' are deposited and patterned using conventional processes, resulting in the structure shown in Figure 7d, which is substantially the same as the structure shown in Figure 6b.

If one employs standard chemical techniques to remove photoresist, the bi-layer resist 66-67 of Fig. 7a may be replaced by a conventional single-layer resist.

Further, the process shown in Fig.'s 7a-d can be modified to produce the sensor structure of Fig. 3 by skipping the steps illustrated in Fig. 7c.

Figure 8 represents a variation designed to maximize the current efficiency of the sensor. In the figure, the MR element 10 has been configured as a triangle so as to eliminate the inefficient upper right hand portion 17 of the MR element. So configured, all current flowing between the contacts 12 will be favorably angled with respect to the at-rest MR element magnetization vector **M**. Current flowing in the corresponding portions 17 of rectangular MR elements, such as shown in Figure 3, operates on less flux than in portions closer to the air bearing surface and further, similar to region 16, has current which flows at angles substantially parallel to **M**. As a result, the operation of the MR sensor in such a region is highly inefficient.

Due to these considerations, the use of a triangular sensor and high resistivity permanent magnetic layer is expected to reduce overall current by a factor of 2, but also is expected to reduce sensor output only 25%, hence the current efficiency of the sensor is enhanced.

The orientation of the MR element's magnetization **M** at boundary 38 of the triangular MR element is directed left to right in the figure so that the respective magnetization vectors of

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the MR element and permanent magnet layers intersect their boundaries at approximately 45°. Even so, because the respective vectors are aligned, flux matching is accomplished using the same amount of permanent magnetic material as with rectangular elements. As a result, the MR element 10 has no unsaturated poles along edge 38 which could lead to domain formation.

Again referring to Figure 3, the location of the read sensitivity "sweet spot" (area of maximum sensitivity) about which the read sensitivity is nearly symmetrical can be effected by lapping, a process necessary in thin film heads to control the throat height of an MR head's thin film writer and to expose the MR element to the head's air bearing surface so that magnetic flux from the disc's surface may enter the MR element efficiently. For example, in the figure, lapping may extend up from the bottom of the figure to a point 30. This would have no effect on the effective location of the left-hand contacts 12' in the figure, but it would move the initial location of the right hand contact to the right in the figure. This movement, in turn, would move the center of the "sweet spot" of the read sensitivity function to the right.

This relative movement of the "sweet spot" causes a problem in aligning the MR element with a thin film writer which is also physically located on the same thin film structure (the writer will typically be formed of thin film layers subsequently formed - see e.g. U.S. patent 4,967,298). The location of the "sweet spot" of the one should be accurately controlled with respect to the "sweet spot" of the other. The shifting of the "sweet spot" due to lapping is therefore undesirable.

A solution to this lapping-induced "sweet spot" shift problem is illustrated in Figure 9. In the figure, the MR element is provided with a narrow extension 32 to the unlapped "air bearing" surface. This extension 32 can be called a "lip". The right hand sense current contact

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12 is provided with an elbow located above the highest point 30 of lapping tolerance so as to form a vertically extending contact edge 34 to the unlapped air bearing surface. So constructed, the width of the "lip" provides the effective read width of the MR element, and the contact structure makes the location of the "sweet spot" invariant to lapping. High resistivity permanent magnet material or isolation gaps prevent disadvantageous current from flowing.

Current flowing from the "lip" contact edge 34 tends to flow perpendicularly from the edge. So directed, this current flow will primarily be directed parallel to the MR element's magnetization vector **M** and thus will provide virtually no component to the sensor's output response to input magnetic flux.

This sensor construction is lapping invariant and also eliminates the inefficient "back portion" 17 of the element as discussed in relation to the triangular element of Fig. 8.

Fig. 10 show a modification to the basic design which eliminates the inefficient "back portion" of the element but which does not have a "lip."

Fig.'s 11 and 12 show a fundamentally different variation. Here the rectangular MR element is rotated approximately 45° and is provided with a "lip" 32. Contacts are applied "squared up" to the air bearing surface rather than slanted as in the original design. Permanent magnetic layers 22 and 24 are provided along the upper left and bottom right edges of the "diamond." All these layers are patterned during manufacture with their magnetization vector **M** directed parallel to the air bearing surface, i.e., left to right in the figure. However, due to induced magnetic "charges" of opposite polarity being produced by the permanent magnetic layers at opposite edges, the magnetization vector **M** of the MR element in the central region rotates so that it is directed between these edges, downward at 45° in the figure. Note

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however, that the magnetization vector **M** of the "lip" remains directed parallel to the air bearing surface. This is due to both the different geometry of the lip and because the magnetization at element edges tends to align itself parallel to the air bearing surface edge.

In the figure, the "lip" is provided with a separate stabilization permanent magnetic layer 40. However, as suggested by Fig. 12, this is a design choice. The "lip" may also be stabilized by extension of the "active region" stabilization layer 22.

Because the permanent magnetic layer and MR element magnetization vectors are not directed in the same direction, the amount of permanent magnetic layer necessary to stabilize the domain structure of the MR element without introducing a longitudinal biasing field must be adjusted. The adjustment is made by multiplying the amount necessary when the vectors are aligned according to the following formula; wherein for a given boundary the permanent magnetic material has a magnetization $M_1$ and a thickness $t_1$, and the MR element has a magnetization $M_2$ and a thickness $t_2$, and the angles between $M_1$ and $M_2$ and the boundary are $\text{theta}_1$ and $\text{theta}_2$ respectively, the amount of permanent magnetic material is chosen such that

$$M_1 * t_1 * \sin(\text{theta}_1) = M_2 * t_2 * \sin(\text{theta}_2).$$

This sensor configuration has two fundamental advantages. First, the sense current contacts may be "squared up" so that they are lapping invariant and still provide a linearized output because sense current **I** and at-rest magnetization **M** will be oriented at approximately

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45°. Second, the sensor has a "lip" which does not "read" at all, but instead acts as a pure flux guide.

Fig. 13 illustrates a variation of this approach wherein the MR element 10 is patterned so that the "left hand" permanent magnetic layer 22 is formed such that the intersecting boundary between the layer 22 and the MR element 10 is direct parallel the MR head's air bearing surface. As illustrated in this figure, the magnetization vectors **M** of the permanent magnetic layers are initially aligned in the same direction as the preferred MR element magnetization layer, downward to the right at 45°. Also, the leftmost sense contact 12 can be configured so that sense current **I** flows only in the substantially rectangular area just above the "lip" as indicated. So configured, the read sensitivity function compares favorably to MR sensors with external transverse biasing - but without the loss in sensitivity caused by the transverse biasing field.

This sensor configuration requires that there be no permanent magnetic stabilization along the left edge of the lip area 32. Stabilization of this edge may instead be accomplished by spacing the sensor's soft magnetic shields close to the MR element at the air bearing surface. Soft magnetic film layers are illustrated in Figure 7a and at 62 and in the above incorporated '035 patent. See layers 15 of Fig. 1 or 23 of Fig. 3a.

Referring back to Fig. 11, which illustrates a "diamond" MR element 10, the "lip" structure can be described as a lapping intolerant "neck" section, connected to a "flux expanding" section, which is in turn is connected to the active sense region where current **I** flows in the MR element between the contacts 12. This lip construction is better illustrated in Fig. 14.

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In this figure, the lip neck region is at reference 46 and the expander region is at reference 48.

This structure is a preferred lip structure with respect to all previously described "lip" embodiments. Although the flux density out of the lip is less than that in, the total sensor output can be increased by virtue of a larger area of interaction with the sensor's sense current. As a result, the read width of the MR sensor can be independently adjusted from the width of the active area so that each may be separately optimized.

Figure 15 illustrates a variation on the sensor structure illustrated in either Fig.'s 9 or 10. In this variation, contact 12' is not canted as is contact 12, but rather is "squared up." The sensor in this configuration yields a more highly symmetrical read sensitivity function than designs with a slanted left contact.

In the figure, the left contact has two approximately orthogonal edges 70 and 72 interfacing with the MR element 10 at a vertex 74 approximately centered on the center of the current from the canted contact 12. One edge 70 is also approximately orthogonal to the air bearing surface defined by lapping up in the figure to point 30.

The aforegoing description has been given by way of example only and it will be appreciated by a person skilled in the art that modifications can be made without departing from the scope of the present invention.

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Claims

1. A magnetoresistive sensor comprising:

a thin film magnetoresistive element (10) having at least one end having unsaturated dipoles in the absence of a stabilising magnetic field, and a magnetisation vector $M_1$ and at least one bias edge not parallel with the magnetisation vector, the magnetoresistive element having a thickness $t_1$ and the magnetisation vector being disposed at an angle $theta_1$ to the bias edge;

contact means (12) for supplying a sense current (I) to the magnetoresistive element;

a thin film permanent magnetic layer (22,24) aligned in a substantially adjacent and co-planar relationship with the bias edge of the magnetoresistive element, the permanent magnetic layer having a thickness $t_2$ and a magnetisation vector $M_2$ being disposed at an angle $theta_2$ to the bias edge;

a gap (26) being provided between the magnetoresistive element and the magnetic layer; and characterised in that

$$M_1 * t_1 * \sin(theta_1) = M_2 * t_2 * \sin(theta_2).$$

2. A magnetoresistive sensor as claimed in claim 1, further comprising an electrical insulator material (23,25) interposed in said gap.

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3. A magnetoresistive sensor as claimed in claim 1 or 2, in which the resistivity of the permanent magnetic layer is substantially higher than the resistivity of the magnetoresistive element.

4. A magnetoresistive sensor as claimed in claim 1 or 2, in which the thickness of the permanent magnetic layer is substantially the same as the thickness of the magnetoresistive element.

5. A magnetoresistive sensor as claimed in claim 4, in which the permanent magnetic layer has a magnetisation vector which is approximately equal to the magnetisation vector of the magnetoresistive element.

6. A magnetoresistive sensor as claimed in any one of the preceding claims, in which said element has a second bias edge substantially parallel to the first bias edge.

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