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MAGNETIC RECORDING MEDIUM



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Technical Field

This invention relates generally to a magnetic recording medium.

Background of the Invention

Conventional magnetic recording media, such as the magnetic recording disks in hard disk drives, typically use a granular ferromagnetic layer, such as a sputter-deposited cobalt-platinum (CoPt) alloy, as the recording medium. Each magnetised domain in the magnetic recording layer is comprised of many small magnetic grains. The transitions between magnetised domains represent the "bits" of the recorded data. US patents 4,789,598 and 5,523,173 describe this type of conventional rigid disk.

As the storage density of magnetic recording disks has increased, the product of the remanent magnetisation M_r (the magnetic moment per unit volume of ferromagnetic material) and the magnetic layer thickness t has decreased. Similarly, the coercive field or coercivity (H_c) of the magnetic layer has increased. This has led to a decrease in the ratio $M_r t / H_c$. To achieve the reduction in $M_r t$, the thickness t of the magnetic layer can be reduced, but only to a limit because the magnetisation in the layer will become more susceptible to thermal decay. This decay has been attributed to thermal activation of small magnetic grains (the superparamagnetic effect). The thermal stability of a magnetic grain is to a large extent determined by $K_u V$, where K_u is the magnetic anisotropy constant of the magnetic layer and V is the volume of the magnetic grain. As the magnetic layer thickness is decreased, V decreases. Thus, if the magnetic layer thickness is too thin, the stored magnetic information will no longer be stable at normal disk drive operating conditions.

One approach to the solution of this problem is to move to a higher anisotropy material (higher K_u). However, the increase in K_u is limited by the point where the coercivity H_c , which is approximately equal to K_u / M_r , becomes too large to be written by a conventional recording head. A similar approach is to reduce the M_r of the magnetic layer for a fixed layer thickness, but this is also limited by the coercivity that can be written. Another solution is to increase the intergranular exchange, so that the effective magnetic volume V of the magnetic grains is increased.

However, this approach has been shown to be deleterious to the intrinsic signal-to-noise ratio (SNR) of the magnetic layer.

Our co-pending application No. 09/416,364, filed October 8, 1999, addresses the thermal stability problem by replacing the conventional single magnetic recording layer with two ferromagnetic films that are antiferromagnetically coupled together across a nonferromagnetic spacer film. Because the magnetic moments of the two antiferromagnetically-coupled films are oriented antiparallel, the net remanent magnetization-thickness product (Mrt) of this recording layer is the difference in the Mrt is accomplished without a reduction in the thermal stability (represented by $K_u V$) of the recording layer because the volume V of the grains in each of the two separate antiferromagnetically-coupled films add constructively. While this approach appears promising, it introduces a new set of unknowns relating to the magnetic and recording/reproducing properties of this unconventional recording layer.

What is needed is a magnetic recording medium that will support very high density recording while retaining good thermal stability, yet can take advantage of the well-known magnetic and recording/reproducing properties of conventional magnetic recording material such as single layer granular Co alloy magnetic material.

Summary of the Invention

Accordingly, the invention provides a magnetic recording disk comprising:

- a substrate;

- a nonferromagnetic underlayer on the substrate;

- a host layer on the underlayer and comprising a first cobalt alloy ferromagnetic film having a thickness t_1 and a magnetization M_1 , a nonferromagnetic spacer film of a material selected from the group consisting of ruthenium (Ru), chromium (Cr), rhodium (Rh), iridium (Ir), copper (Cu), and their alloys formed on and in contact with the first ferromagnetic film, and a second cobalt alloy ferromagnetic film formed on and in contact with the spacer film and having a thickness t_2 and a magnetization M_2 , the spacer film having a thickness sufficient to induce the second ferromagnetic film to be exchange coupled antiferromagnetically to the first ferromagnetic film across the spacer film, and wherein the magnetic moments per unit area ($M_1 \times t_1$) and ($M_2 \times t_2$) of the first and second ferromagnetic films, respectively, are different from one another;

a magnetic recording layer on and in contact with the second ferromagnetic film of the host layer, the magnetic recording layer having a composition different from the composition of the second ferromagnetic film and being ferromagnetically coupled with the second ferromagnetic film; and

a protective overcoat formed on the magnetic recording layer.

For a fuller understanding of the nature and advantages of the present invention, reference should be made to the following detailed description of an embodiment thereof taken together with the accompanying figures.

Brief Description of the Drawing

Fig. 1 is a schematic sectional view of a prior art magnetic recording disk with a single-layer magnetic recording layer.

Fig. 2 is a schematic sectional view of a magnetic recording disk of an embodiment of the present invention.

Detailed Description of the Invention

Fig. 1 illustrates the cross sectional layer structure of a prior art disk 10 with a single layer Co alloy magnetic recording layer 15. The thin film layers are sputter deposited onto at least one and preferably both planar surfaces of the substrate 11 to form the data recording areas of the disk. The disk substrate 11 may be made of any suitable material, such as glass, SiC/Si, ceramic, quartz, or an AlMg alloy base with a NiP surface coating. The seed layer 12 is an optional layer that may be used to improve the growth of the underlayer 13 and thus the magnetic properties of the magnetic layer 14, such as its coercivity. The seed layer 12 is most commonly used when the substrate 11 is nonmetallic, such as glass. The seed layer 12 has a thickness in the range of approximately 5 to 50 nm and is one of the materials, such as Ta, CrTi or NiAl, which are known in the prior art to be useful as seed materials for promoting the growth of subsequently deposited layers in certain preferred crystalline orientations. The underlayer 13 is deposited onto the seed layer, if present, or otherwise directly onto the substrate 11, and is a nonmagnetic material such as chromium or a chromium alloy, such as CrV or CrTi. Variations in the thickness of the underlayer 13 result in changes in the magnetic characteristics of the magnetic layer 15, such as its coercivity. The underlayer 13 has a thickness in the range of 1 to 100 nm with a typical value being approximately 20 nm.

Before the deposition of the magnetic layer 15, a very thin (typically 0.5 to 5 nm) Co alloy onset or nucleation layer 14 is typically deposited on the underlayer 13. The nucleation layer 14 has a composition selected to enhance the growth of the hexagonal close-packed (HCP) Co alloy magnetic layer 15 so that its C-axis is oriented in the plane of the layer. The nucleation layer 14 may be a CoCr alloy with a Cr composition selected so as to make the layer 14 nonferromagnetic or very slightly ferromagnetic. Alternatively, the nucleation layer 14 may be a ferromagnetic Co alloy, in which case the nucleation layer 14 will affect the magnetic properties of the magnetic layer 15. The Co alloy magnetic recording layer 15 may be a CoPtCrB alloy with 4 to 25 atomic percent (at.%) platinum, 10 to 23 at.% chromium and 2 to 20 at.% boron. If the magnetic layer 15 is CoPtCrB, then the nucleation layer 14 may be CoPtCr or CoPtCrB with B less than 6 at.%. The magnetic layer 15 typically has a thickness in the range of 5 to 20 nm.

The protective overcoat 16 may be a typical overcoat of essentially amorphous carbon optionally doped with hydrogen and/or nitrogen. The

overcoat is typically less than 15 nm thick. All of the layers described above from the seed layer 12 to the overcoat 16 can be sputtered in a continuous process in either an in-line sputtering system or a single disk system, such as commercially available single disk systems with multiple sputtering target capacity. The sputter deposition of each of the layers can be accomplished using standard targets and techniques known to those in the field with the modifications described above.

Preferred Embodiments

The magnetic recording medium of the present embodiment has a magnetic recording layer formed on a special multilayered host layer. The host layer comprises at least two ferromagnetic films that are exchange-coupled antiferromagnetically (AF) to one another across a nonferromagnetic spacer film.

In the preferred embodiment the two AF-coupled films of the host layer have magnetic moments that are substantially equal in magnitude but are oriented antiparallel so that the host layer has substantially no net magnetic moment. However, the host may layer may have some nonzero net magnetic moment because of the difficulty in fabricating the films to precise thicknesses.

A magnetic recording disk 20 according to the present invention is depicted in the cross-section schematic shown in Fig. 2, wherein the host layer 30 has replaced the onset or nucleation layer 14 of the prior art structure of Fig. 1. As shown schematically in Fig. 2 the recording layer 25 is deposited on the host layer 30. Host layer 30 is made up of two ferromagnetic films 32, 34 separated by a nonferromagnetic spacer film 36. The nonferromagnetic spacer film 36 has a thickness and composition chosen so that the magnetic moments 42, 44 of adjacent films 32, 34, respectively, are AF-coupled through the nonferromagnetic spacer film 36 and are antiparallel in zero applied magnetic fields. The ferromagnetic films 32, 34 have magnetic moment values of $M_{r1} t_1$ and $M_{r2} t_2$, respectively, wherein $M_{r1} t_1$ and $M_{r2} t_2$ are approximately equal. (Because the remanent magnetisation M_r is expressed as the magnetic moment per unit volume of ferromagnetic material, the product $M_r t$ is the magnetic moment per unit area for a magnetic layer of thickness t).

In the preferred embodiment each of the ferromagnetic films 32, 34 has substantially the same thickness t and is made of substantially the same ferromagnetic material so as to have the same M_r . Thus the magnetic

moments 42, 44 essentially compensate or cancel each other, so that the host layer 30 has substantially no net magnetic moment.

The AF coupling of ferromagnetic films via a nonferromagnetic transition metal spacer film has been extensively studied and described in the literature. In general, the exchange coupling oscillates from ferromagnetic to antiferromagnetic with increasing spacer film thickness. This oscillatory coupling relationship for selected material combinations is described by Parkin et al. in "Oscillations in Exchange Coupling and Magnetoresistance in Metallic Superlattice Structures: Co/Ru, Co/Cr and Fe/Cr", *Phys. Rev. Lett.*, Vol. 64, p. 2034 (1990). The material combinations include ferromagnetic films made of Co, Fe, Ni, and their alloys, such as Ni-Fe, Ni-Co, and Fe-Co, and nonferromagnetic spacer films such as ruthenium (Ru), chromium (Cr), rhodium (Rh), iridium (Ir), copper (Cu), and their alloys. For each such material combination, the oscillatory exchange coupling relationship has to be determined, if not already known, so that the thickness of the nonferromagnetic spacer film is selected to assure antiferromagnetic coupling between the two ferromagnetic films. The period of oscillation depends on the nonferromagnetic spacer material, but the strength and phase of the oscillatory coupling also depends on the ferromagnetic material and interfacial quality. The oscillatory antiferromagnetic coupling of ferromagnetic films has been used in spin-valve type giant magnetoresistance (GMR) recording heads to design continuous magnetised antiferromagnetically coupled films whose magnetic moments are rigidly coupled together antiparallel during operation of the head. These type of spin-valve structures are described, for example, in US patents 5,408,377 and 5,465,185. This type of magnetic structure of two ferromagnetic films antiferromagnetically coupled across a very thin nonferromagnetic spacer film, such as used in spin-valve heads and shown in the host layer 30 structure of Fig. 2, is also called a "synthetic antiferromagnet". In the case where the structure has no net magnetic moment because the moments from the individual ferromagnetic films cancel, the structure can be called a "compensated" synthetic antiferromagnet.

For this AF-coupled structure of host layer 30 the orientations of the magnetic moments 42, 44 of adjacent films 32, 34, respectively, are aligned antiparallel and thus add destructively. The arrows 42, 44 represent the moment orientations of individual magnetic domains that are directly above and below one another across the AF coupling film 36. In the absence of an applied magnetic field, the bottom ferromagnetic film 34 on underlayer 23 will have a granular structure with individual magnetic

domains having their moments essentially randomly oriented in the plane of the film. The grains of ferromagnetic film 32 form magnetic domains with moment orientations that are antiparallel to the moment orientations of ferromagnetic film 34 that are directly across the AF coupling film 36.

The type of ferromagnetic material and the thickness values t_1 , t_2 of the ferromagnetic films 32, 34 are chosen so that the net moment in zero applied field will be essentially zero. The Mrt for the host layer 30 is given by $Mr_1 t_1 - Mr_2 t_2$. In the preferred embodiment, $Mr_1 t_1$ should be equal to $Mr_2 t_2$. This may be accomplished by using the same ferromagnetic materials in the two films 32, 34 and having t_1 be the same as t_2 . If different ferromagnetic material compositions are used in the two films 32, 34 so that the magnetization (the magnetic moment per unit volume of material) of the two ferromagnetic films is made different, then the thicknesses are adjusted accordingly. While Fig. 2 is shown for a host layer 30 with two-film structure with a single spacer film, the invention is extendible to host layer structures with multiple spacer films and multiple ferromagnetic films.

The magnetic recording layer 25 is deposited directly on the top ferromagnetic film 32, which also acts as the onset or nucleation layer for the magnetic layer 25. Because the host layer 30 is intended to function as a compensated synthetic antiferromagnet, the composition of the magnetic layer 25 on top of film 32 must be different from the composition of film 32. In the preferred embodiment the magnetic layer 25 is a CoPtCrB alloy and the ferromagnetic films 32, 34 of host layer 30 are also a CoPtCrB alloy, but with a different composition, e.g. B is present in an amount significantly less than in the magnetic layer 25. Alternatively, films 32, 34 may be a CoCr alloy or a CoPtCr alloy. The films 32, 34 may have a thickness in the range of 0.5 to 5 nm. The nonferromagnetic spacer film 36 in host layer 30 is a 0.6 nm Ru film. The Ru spacer film thickness was chosen to be at the first antiferromagnetic peak in the oscillatory coupling relationship. It may also be desirable for each of the CoPtCrB ferromagnetic films 32, 34 to include an interface film consisting essentially of 0.5 nm of Co at the interface with the Ru spacer film 36. These ultra-thin Co films increase the interfacial moment between the ferromagnetic films and the spacer film, resulting in enhanced antiferromagnetic coupling. However, antiferromagnetic exchange coupling will occur without incorporating the Co interface films in the CoPtCrB ferromagnetic films 32, 34.

The top ferromagnetic film 32 is exchange coupled ferromagnetically to the magnetic layer 25 and weakly coupled antiferromagnetically to the bottom ferromagnetic film 34 across the spacer film 36. When the magnetic field from the write head switches the magnetization direction of grains in the magnetic layer 25, the magnetization direction of the top film 32 will also switch because of the exchange coupling with those grains. The magnetization direction of the bottom film 34 will also switch due to its weak antiferromagnetic coupling to top film 32. Thus the moments of films 32, 34 will remain antiparallel regardless of the magnetization direction of the grains in the magnetic layer 25 on top of the host layer 30.

The enhanced thermal stability of the preferred embodiment composite structure (magnetic layer 25 together with host layer 30) compared to a single magnetic layer arises because the anisotropy of the grains in both films 32 and 34 are substantially uniaxial, and thus can add constructively even if the magnetic moments of films 42, 44 are antiparallel. The magnetic volume V of the composite structure that determines the thermal stability will be approximately the sum of the volumes of the grains in the magnetic layer 25 and the AF-coupled films 32 and 34. However, the magnetic moment of the composite structure is just the moment from magnetic layer 25 because the host layer 30 has essentially no net magnetic moment. The antiferromagnetic coupling between the two ferromagnetic films 32, 34 provides a mechanism to increase the effective film thickness of the composite structure while reducing the net Mrt value of the composite structure. Thus the ferromagnetic films can contain very small diameter grains and maintain thermal stability.

In an alternative embodiment the two AF-coupled films of the host layer have magnetic moments that are still oriented antiparallel but are deliberately different in magnitude so that the host layer has a net non-zero magnetic moment (Mr_1t_1 not equal to Mr_2t_2). One reason for such an embodiment is that the optimum recording performance level of the structure may occur at a point where the thickness of the lower ferromagnetic film in the host layer is not equal to the thickness of the upper ferromagnetic film. If the same materials are used in both these films ($Mr_1 = Mr_2$) then Mr_1t_1 is not equal to Mr_2t_2 . This case may occur if it is necessary to keep the top film of the host layer thin enough that it does not generate recording noise for the magnetic recording layer, while it is necessary to make the bottom film of the host layer thick enough to more strongly develop the desired in-plane C-axis orientation. A second

reason for the alternative embodiment relates to thermal stability of the media. A recorded magnetic transition in the media produces a magnetic field in a direction which tends to demagnetise adjacent transitions, and thus facilitate thermal decay. In the host layer of the present invention, a transition will be created in the lower ferromagnetic film which will create a field which opposes this demagnetisation field, and thus reduce thermal decay. A third reason for the alternative embodiment is to adjust the signal level or Mrt of the media. It is typical in the disk drive industry to design the disk according to requested values of Mrt and coercivity (H_c). However, Mrt and H_c are correlated. Therefore, for a given Mrt value, to reach the H_c design point of the media the conventional approach is to change the process conditions, such as underlayer thickness or deposition temperature, which can be deleterious to the recording properties. With the present invention the Mrt can be adjusted through a different method, namely changing the relative values of Mr_1t_1 and Mr_2t_2 .

What is claimed is

1. A magnetic recording disk comprising:
 - a substrate;
 - a nonferromagnetic underlayer on the substrate;
 - a host layer on the underlayer and comprising a first cobalt alloy ferromagnetic film having a thickness t_1 and a magnetization M_1 , a nonferromagnetic spacer film of a material selected from the group consisting of ruthenium (Ru), chromium (Cr), rhodium (Rh), iridium (Ir), copper (Cu), and their alloys formed on and in contact with the first ferromagnetic film, and a second cobalt alloy ferromagnetic film formed on and in contact with the spacer film and having a thickness t_2 and a magnetization M_2 , the spacer film having a thickness sufficient to induce the second ferromagnetic film to be exchange coupled antiferromagnetically to the first ferromagnetic film across the spacer film, and wherein the magnetic moments per unit area ($M_1 \times t_1$) and ($M_2 \times t_2$) of the first and second ferromagnetic films, respectively, are different from one another;
 - a magnetic recording layer on and in contact with the second ferromagnetic film of the host layer, the magnetic recording layer having a composition different from the composition of the second ferromagnetic film and being ferromagnetically coupled with the second ferromagnetic film; and
 - a protective overcoat formed on the magnetic recording layer.
2. The disk of claim 1 wherein the first and second ferromagnetic films are formed of the same material, and wherein t_1 is different from t_2 .
3. The disk of claim 1 wherein the first and second ferromagnetic films are formed of different materials and wherein t_1 and t_2 are substantially the same thickness.
4. The disk of claim 1 wherein the first ferromagnetic film of the host layer includes an interface film consisting essentially of cobalt and being in contact with the spacer film.
5. The disk of claim 1 wherein the second ferromagnetic film of the host layer includes an interface film consisting essentially of cobalt and being in contact with the spacer film.