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LAMINATED MAGNETIC RECORDING MEDIA

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Field of the Invention

This invention relates generally to magnetic recording media, and more particularly to thermally stable high density media.

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 magnetized domain in the magnetic layer is comprised of many small magnetic grains. The transitions between magnetized domains represent the "bits" of the recorded data. IBM's 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 magnetization Mr(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 Mrt/H_c. To achieve the reduction in Mrt, the thickness t of the magnetic layer can be reduced, but only to a limit because the layer will exhibit increasing magnetic decay, which 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_uV, where K_u is the magnetic anisotropy constant of the layer and V is the volume of the magnetic grain. As the layer thickness is decreased, V decreases. If the 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/Mr, becomes too great to be written by a conventional recording head. A similar approach is to reduce the Mr 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.

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

GB Patent Application 2355018 disclosures a magnetic recording media with anti-ferromagnetically coupled ferromagnetic films as the recording layer.

Magnetic recording media with high intrinsic SNR (low intrinsic media noise) is desirable because it is well known in metal alloy media, such as CoPt alloys, that the intrinsic media noise increases with increasing linear recording density. Media noise arises from irregularities in the magnetic transitions and results in random shifts of the readback signal peaks. These random shifts are referred to as "peak jitter" or "time jitter". Thus higher media noise leads to higher bit error rates. It is therefore desirable to develop a thin film metal alloy magnetic media that generates noise below a maximum acceptable level so that data can be recorded at maximum linear density. It is known that substantially improved SNR can be achieved by replacing a single magnetic layer with a laminated magnetic layer of two (or more) separate magnetic layers that are spaced apart by an nonmagnetic spacer layer. This discovery was made by S. E. Lambert, et al., "Reduction of Media Noise in Thin Film Metal Media by Lamination", *IEEE Transactions on Magnetics*, Vol. 26, No. 5, September 1990, pp. 2706-2709, and subsequently patented in IBM's U.S. patent 5,051,288. The reduction in media noise by lamination is believed due to a decoupling of the magnetic interaction or exchange coupling between the magnetic layers in the laminate. The use of lamination for noise reduction has been extensively studied to find the favorable spacer layer materials, including Cr, CrV, Mo and Ru, and spacer layer thicknesses, from 5 to 400 Å, that result in the best decoupling of the magnetic layers , and thus the lowest media noise. This work has been reported in papers by E. S. Murdock, et al., "Noise Properties of Multilayered Co-Alloy Magnetic Recording Media", *IEEE Transactions on Magnetics*, Vol. 26, No. 5, September 1990, pp. 2700-2705; A. Murayama, et al., "Interlayer Exchange Coupling in Co/Cr/Co Double-Layered Recording Films Studied by Spin-Wave Brillouin Scattering", *IEEE Transactions on Magnetics*, Vol. 27, No. 6, November 1991, pp. 5064-5066; and S. E. Lambert, et al., "Laminated Media Noise for High Density Recording", *IEEE Transactions on Magnetics*, Vol. 29, No. 1, January 1993, pp. 223-229. U.S. patent 5,462,796 and the related paper by E. Teng et al., "Flash Chromium Interlayer for High Performance Disks with Superior Noise and Coercivity Squareness", *IEEE Transactions on Magnetics*, Vol. 29, No. 6, November 1993, pp. 3679-3681, describe a laminated low-noise

disk that uses a discontinuous Cr film that is thick enough to reduce the exchange coupling between the two magnetic layers in the laminate but is so thin that the two magnetic layers are not physically separated.

What is needed is magnetic recording media that will support very high density recording while retaining good thermal stability and SNR.

Disclosure of the Invention

The invention is a magnetic recording medium wherein the magnetic recording layer is at least two ferromagnetic films antiferromagnetically (AF) 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 the recording layer is the difference in the Mrt values of the two ferromagnetic films. This reduction in Mrt is accomplished without a reduction in the thermal stability of the recording medium because the volumes of the grains in the antiferromagnetically-coupled films add constructively. The medium also enables much sharper magnetic transitions to be achieved with reduced demagnetization fields, resulting in a higher linear bit density for the medium. In one embodiment the magnetic recording medium comprises two ferromagnetic films, each a granular film of a sputter deposited CoPtCrB alloy, separated by a Ru spacer film having a thickness to maximize the antiferromagnetic exchange coupling between the two CoPtCrB films. One of the ferromagnetic films is made thicker than the other, but the thicknesses are chosen so that the net moment in zero applied magnetic field is low, but nonzero.

The AF-coupled magnetic recording layer of the present invention, i.e., at least two ferromagnetic films antiferromagnetically coupled together across a nonferromagnetic spacer film, can be used as the individual magnetic layers in the laminated medium described in the above-cited '288 patent to produce a medium with both thermal stability and low intrinsic media noise.

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

Brief Description of the Drawing

Fig. 1 is a schematic sectional view of the antiferromagnetically (AF) coupled magnetic recording layer in a recording medium;

Fig. 2A is a schematic illustration of the AF-coupled layer illustrating the orientations of the moments of the ferromagnetic films at a recorded magnetic transition;

Fig. 2B is a graph of calculated magnetic field above the AF-coupled layer and a single layer (SL) medium as a function of downtrack position from a transition;

Fig. 3 is a schematic sectional view of a disk structure illustrating the substrate, underlayer, the films in the AF-coupled layer, and the protective overcoat;

Fig. 4 is a magnetic hysteresis loop for the structure with the AF-coupled layer of Fig. 3;

Fig. 5 is a schematic sectional view of a prior art laminated disk structure with conventional individual single layers as the magnetic layers in the laminate; and

Fig. 6 is a schematic sectional view of a laminated disk structure with AF-coupled layers as the individual magnetic layers in the laminate.

Detailed Description of the Invention

A magnetic recording medium has a recording layer formed of two or more ferromagnetic films that are exchange-coupled antiferromagnetically (AF) to their neighboring ferromagnetic films by one or more nonferromagnetic spacer films. This is shown schematically in Fig. 1 for a recording layer 10 made up of two ferromagnetic films 12, 14 separated by a nonferromagnetic spacer film 16. The nonferromagnetic spacer film 16 thickness and composition are chosen so that the magnetic moments 22, 24 of adjacent films 12, 14, respectively, are AF-coupled through the nonferromagnetic spacer film 16 and are antiparallel in zero applied fields.

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 magnetized 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 IBM patents 5,408,377 and 5,465,185. The '185 patent describes a structure used in many commercially available spin-valve GMR heads, namely a laminated antiparallel-pinned ferromagnetic layer having ferromagnetic films whose moments are rigidly coupled together and remain stationary during operation of the head.

The films 12, 14 have magnetic moment values of $Mr_1\ t_1$ and $Mr_2\ t_2$, respectively. (Because the remanent magnetization Mr is expressed as the magnetic moment per unit volume of ferromagnetic material, the product Mrt is the magnetic moment per unit area for a magnetic layer of thickness t.) For this AF-coupled structure the orientations of the magnetic moments 22, 24 of adjacent films 12, 14, respectively, are aligned antiparallel and thus add destructively to reduce the magnetic moment of the composite layer 10. The arrows 22, 24 represent the moment orientations of individual magnetic domains that are directly above and below one another across the AF coupling film 16. In the absence of an applied magnetic field, when the ferromagnetic film 14 is deposited onto the medium substrate, it will have a granular structure with multiple adjacent grains being coupled together to form individual magnetic domains. In the absence of an applied magnetic field the moments of these domains in film

14 will be essentially randomly oriented. The spacer film or AF-coupling film 16 is then deposited to the correct thickness directly on ferromagnetic film 14. Next, the second ferromagnetic film 12 is deposited directly on the AF coupling film 16. As the grains of ferromagnetic film 12 grow they will form magnetic domains with moment orientations that are antiparallel to the moment orientations of ferromagnetic film 14 that are directly across the AF coupling film 16.

The type of ferromagnetic material and the thickness values t_1, t_2 of the ferromagnetic films 12, 14 are chosen so that the net moment in zero applied field will be low, but nonzero. For the case shown in Fig. 1, the Mrt for the structure is given by $Mr_1 t_1 - Mr_2 t_2$. $Mr_1 t_1$ should be $> Mr_2 t_2$. This may be accomplished by using the same ferromagnetic materials in the two films 12, 14 and having t_1 be greater than t_2, or the magnetization (the magnetic moment per unit volume of material) of the two ferromagnetic films may be made different by using different ferromagnetic materials for the two films. While Fig. 1 is shown for a two-film structure with a single spacer film 16, structures with multiple spacer films and multiple ferromagnetic films may be used.

The magnetic layer described above has a number of advantages over a magnetic layer formed as a single layer of ferromagnetic material. Low remanent magnetization can be obtained without using ultra-thin magnetic layers or low-magnetization alloys. This avoids the problems of thermal instability and difficulty in writing discussed above. If the magnetic layer in Fig. 1 is compared to a single-layer consisting of only film 12, for example, the addition of the AF-coupled ferromagnetic film 14 reduces the net magnetic moment of the composite structure without decreasing either the thickness or the magnetization of film 12.

The enhanced thermal stability of the composite structure compared to a single magnetic layer arises because the anisotropy of the grains in both films 12 and 14 are substantially uniaxial, and thus can add constructively even if the magnetic moments of films 12, 14 are antiparallel. The resulting stability parameter of the coupled system K_uV is given by $Ku_1V_1 \setminus KuV \setminus (Ku_1V_1+Ku_2V_2)$, where Ku_1V_1 and Ku_2V_2 are the anisotropy energies of typical grains in films 12, 14, respectively. The upper limit for the composite stability parameter $KuV = Ku_1V_1+Ku_2V_2$ will be achieved for the case when magnetic grains in film 12 and 14 are strongly coupled and share a common anisotropy axis direction. The magnetic volume V of the composite structure (layer 10) that determines the thermal stability will be approximately the sum of the volumes of the

exchange-coupled grains in films 12 and 14, whereas the magnetic moment of layer 10 is the difference of the individual moments of films 12, 14. The antiferromagnetic coupling between the two ferromagnetic films provides a mechanism to increase the effective film thickness while reducing the net Mrt value of the composite structure. Thus the ferromagnetic films can contain very small diameter grains and maintain thermal stability.

An AF-coupled medium is shown schematically in Fig. 2A with a recorded or written magnetic transition. The plus (+) and minus (-) symbols represent the magnetic poles arising from the transition. The calculated longitudinal field (H_x) 10 nm above the surface of the AF-coupled medium is shown in Fig. 2B as a function of X direction or downtrack position from the transition. The moment and thickness values for the two films 12, 14 and the calculated Mrt for the AF-coupled layer are listed in Fig. 2B. For comparison, Fig 2B also shows model calculations of longitudinal magnetic field arising from transitions in a single-layer (SL) medium that has a similar Mrt. The thickness values (t_1 and t_2) were chosen such that the peak longitudinal field was the same for the AF-coupled medium compared to the SL medium. The total thickness of the ferromagnetic material in the AF-coupled medium is 2.7 times thicker. Therefore, the AF-coupled medium should be more thermally stable than the SL medium. The longitudinal field profile in the downtrack direction decays faster for the AF-coupled medium, resulting in a sharper transition. This indicates that the transitions can be spaced closer than in the SL medium, resulting in a higher linear bit density for the medium. While not shown in Fig. 2B, calculations have also shown that the demagnetization field from a transition within the AF-coupled medium also decreases faster than in the SL medium. In addition, the magnitude and sign of the demagnetization field depends on the Y position (see Fig. 2A) within the medium. Thus for certain Y positions within the medium, the demagnetization field is reduced to zero. Small demagnetization fields are desired because they can affect other transitions and cause the transition to demagnetize itself.

Fig. 3 shows an example structure of conventional CoPtCrB longitudinal recording media alloys being used for the ferromagnetic films. The structure was fabricated using conventional sputter deposition equipment and processes. The films forming the structure were grown onto a Cr underlayer deposited onto a substrate of a AlMg disk blank with a nickel-phosphorous (NiP) surface coating, with the substrate temperature at approximately 200 âC. The ferromagnetic films are CoPtCrB, with the top film corresponding to film 12 in Fig. 1 being thicker than the bottom

ferromagnetic film corresponding to film 14 in Fig. 1 (12 nm vs. 7 nm). The nonferromagnetic spacer film is a 0.6 nm Ru film. As with single-layer media, it is advantageous to use a granular ferromagnetic material with isolated magnetic grains to lower the media noise. The Ru film thickness was chosen to be at the first antiferromagnetic peak in the oscillatory coupling relationship. For this example, each CoPtCrB ferromagnetic film included an interface film consisting essentially of 0.5 nm of Co at the interface with the Ru film. These ultra-thin Co films increase the interfacial moment between the ferromagnetic films and the Ru film, resulting in enhanced antiferromagnetic coupling. However, antiferromagnetic exchange coupling has been demonstrated without incorporating the Co interface films in the CoPtCrB ferromagnetic films.

Fig. 4 shows the major hysteresis loop (solid line) and the remanent hysteresis loop (dashed line) measured at T=350 âK for the structure of Fig. 3. Referring first to the remanent hysteresis loop, it is obtained by saturating the AF-coupled layer in a positive field and then applying an increasing reverse negative field and measuring the remanent moment in the layer after the negative field is applied. The remanent loop is a plot of the remanent moment versus the magnitude of the reverse field. For this sample the remanent loop shows Mrt=0.21, the remanent coercive field H_{cr}=3.2 kOe, and S'=0.92 at room temperature, where S' is a measure of the slope of the remanent loop at H_{cr}. For comparison, a similarly grown 15-nm single layer of the same CoPtCrB alloy has properties of Mrt=0.38, H_{cr}=2.4 kOe and S'=0.76 at room temperature. Thus, the AF-coupled medium allows a significantly lower Mrt to be achieved with a greater total magnetic layer thickness.

Referring next to the major hysteresis loop of Fig. 4, the pairs of horizontal arrows indicate the orientation of the ferromagnetic films in the AF-coupled layer at different points in the hysteresis loop. The applied field is increased in the positive direction (arrows 30, 32). For large applied fields (>3000 Oe), the antiferromagnetic coupling is overcome and the moments of the two ferromagnetic films are both parallel to the applied field (arrows 42, 44). As the applied field is reduced (arrow 34) the moment of the thinner bottom ferromagnetic film reverses and becomes antiparallel to the moment of the thicker top ferromagnetic film (arrows 52, 54) and to the applied field with a drop in the net moment. This switch occurs roughly at the exchange field felt by the bottom film (H_{ex2}=2000 Oe) arising from the coupling across the Ru film. The value of $H_{ex2} = J_{ex}/M_2\, t_2$, where J_{ex} is the antiferromagnetic interface exchange energy density across the Ru spacer layer and M_2 and t_2 are the

magnetization and thickness of the bottom ferromagnetic film, respectively. For an antiparallel alignment of the ferromagnetic films to be realized requires that H_{ex2} exceed the coercive field required to reverse the bottom ferromagnetic film (H_{c2}). H_{c2} is the coercive field of the bottom film, assuming no exchange interaction with the top ferromagnetic film. Thus, the magnetic properties and thickness of the bottom film, as well as the AF-coupling film, must be designed to maintain $H_{ex2}>H_{c2}$.

The remanent state after saturation in a positive field is given by the moment of the top ferromagnetic film parallel to the field direction and the moment of the bottom ferromagnetic film antiparallel to the positive field direction (arrows 52, 54). In a reverse applied field (arrow 36), the magnetic state is stable until the moment of the top ferromagnetic film reverses and the moments of both films are parallel and aligned in the negative saturation state (arrows 62, 64). The switching of the moment of the top ferromagnetic film determines the coercive field of the AF-coupled layer and is given by $H_c = H_{ex1} + H_{c1}$ where H_{ex1} is the exchange field acting on the top ferromagnetic film ($H_{ex1}=J_{ex}/M_1t_1$) and H_{c1} is the coercive field of the top ferromagnetic film, assuming no interaction with the bottom ferromagnetic film. Thus, the properties of the top ferromagnetic film and the AF-coupling film must be designed to maintain H_c of the composite structure below the expected write field of the head. For this example the pathway to go from one remanent state (arrows 52, 54) to the next remanent state (arrows 72, 74) goes through an intermediate state where the moments of the two films are parallel (arrows 62, 64). Thus, in contrast to AF-coupled structures used in spin-valve GMR recording heads, the moments of the ferromagnetic films in the medium according to the present invention are not rigidly coupled together across the AF-coupling film because the coupling must be overcome to write on the medium. The hysteresis loop of Fig. 4 exhibits the desired feature of an AF-coupled layer, i.e., a low remanent magnetization relative to the saturation magnetization.

Recording performance tests on the AF-coupled layer were performed using a conventional longitudinal recording head. Signal to noise ratio measurements determined a media S_oNR of 31.9 dB at 9500 flux changes per millimeter (fc/mm), where S_o is the isolated pulse amplitude and N is the integrated media noise at 9500 fc/mm recording density. These results demonstrate the viability of AF-coupled magnetic layers for data storage.

The AF-coupled media according to the present invention has also been demonstrated for structures with and without one or both Co interface films, with and without one or both CoCr interface layers, and with CoCrPtTa ferromagnetic films.

Laminated Media with AF-coupled Layers

Laminated magnetic recording media, based on the invention described in the previously cited '288 patent, have also been fabricated with the AF-coupled (AFC) layers described above as the individual magnetic layers in the laminate. Fig. 5 is a schematic of a conventional laminated magnetic recording medium wherein the magnetic recording layer 30 comprises at least two individual magnetic layers 32, 34, each with a magnetic moment (per unit area) of Mrt1, where two neighboring layers are separated by a nonferromagnetic spacer layer 36. This composite structure has a total Mrt = 2Mrt1 for a two-layer laminate. (For ease in explanation it will be assumed that all ferromagnetic layers have the same composition, so that Mr is the same. However, it is within the scope of the invention that different ferromagnetic materials may be used, in which case the total magnetic moment would be given by $Mr_1 t_1 + Mr_2 t_2$ for the structure of Fig. 5.)

The new laminated media using the AFC layers is depicted schematically in Fig. 6 for a structure with two AFC layers and one nonferromagnetic spacer layer. In the laminated AFC magnetic media of Fig. 6, the magnetic recording layer 30' comprises AFC layers 32', 34' separated by nonferromagnetic spacer layer 36'. The individual AFC layers 32', 34' replace the corresponding magnetic layers 32, 34 (Fig. 5). Each AFC layer 32', 34' is made up to two films (42, 44 and 52, 54, respectively) antiferromagnetically coupled by antiferromagnetically coupling films (46, 56, respectively) such that the net Mrt of each AFC layer is given by Mrt_1-Mrt_2. This allows control of the Mrt independent of either Mr or t. As explained above for the non-laminated AFC media, thermally stable, low Mrt magnetic media can be obtained. In the new laminated structure, as depicted in Fig. 6, the composite Mrt is $2*(Mrt_1-Mrt_2)$. By changing the relative magnitude of Mrt_1 and Mrt_2, the Mrt of the composite laminated structure can be tuned without suffering thermal instabilities. Therefore, thermally stable, low-Mrt laminated media can be obtained. Of course, while only two AFC layers are depicted in Fig. 6, the laminated AFC media of the present invention may have three or more AFC layers, with nonferromagnetic spacer layers located between neighboring AFC layers.

A series of conventional single-layered media, non-laminated AFC media, and laminated AFC media structures were fabricated on two types of commercially available disk substrates, glass and NiP/AlMg metal, to compare the intrinsic media SNR. The structures on glass substrates were grown on a NiAl/Cr/$Co_{63}Cr_{37}$ underlayer structure. The structures on NiP/AlMg substrates were grown on a Cr/$Co_{63}Cr_{37}$ underlayer structure.

For these tests, the magnetic layer composition of all the magnetic films was $Co_{62}Pt_{10}Cr_{22}B_6$. The antiferromagnetically coupling films 46, 56 used in the AFC layers 32', 34', respectively were 6 Å Ru layers. The nonferromagnetic spacer layer 36' was also Ru, but with thicknesses ranging from 12 to 48 Å. In the laminated AFC media, the nonferromagnetic spacer layer 36' between the two AFC layers 32', 34' is selected to have a composition and thickness so that there is no significant ferromagnetic or antiferromagnetic coupling between the two adjacent ferromagnetic films 44 and 52. For known materials, the thickness of the spacer layer 36' can be readily determined because it is known from the oscillatory coupling curve how the exchange coupling oscillates from ferromagnetic to antiferromagnetic with increasing spacer layer thickness. In the cited '288 patent the Cr spacer film between the two Co alloy films had a thickness of 40 Å or greater, which is well beyond any detectable ferromagnetic or antiferromagnetic exchange coupling peak on the oscillatory coupling curve. For $Co_{62}Pt_{10}Cr_{22}B_6$ alloy ferromagnetic films and Ru, a Ru thickness greater than approximately 10 Å, which is beyond the first antiferromagnetic peak on the oscillatory coupling curve, is sufficient to assure no significant ferromagnetic or antiferromagnetic coupling. This requirement for the spacer layer is in direct contrast to the requirement for the antiferromagnetic coupling films 46, 56, each of which is selected to have a thickness and composition corresponding to the first antiferromagnetic peak of the oscillatory coupling curve.

The AFC layers in both the laminated and non-laminated AFC media structures were designed to have an Mrt=Mrt1-Mrt2=0.20 memu/cm². The laminated AFC media with two individual AFC layers (Fig. 6) thus had a total Mrt=0.40 memu/cm². The conventional media with a single CoPtCrB layer was fabricated to have Mrt = 0.38 memu/cm². The measured SNR for these structures is shown in Table 1 (glass substrates) and Table 2 (metal substrates) below:

Table 1

(Glass Substrates)

SAMPLE	*Mrt (memu/cm²)*	*Media SNR (dB)*
CoPtCrB conventional single layer	0.38	32.3
Non-laminated AFC	0.2	31.5
Laminated AFC/12 Å Ru spacer	0.4	33.3
Laminated AFC/24 Å Ru spacer	0.4	33.3
Laminated AFC/48 Å Ru spacer	0.4	33.2

Table 2

(Metal Substrates)

SAMPLE	*Mrt (memu/cm²)*	*Media SNR (dB)*
Non-laminated AFC	0.24	32.4
Laminated AFC/12 Å Ru spacer	0.4	34.6
Laminated AFC/24 Å Ru spacer	0.39	34.8
Laminated AFC/36 Å Ru spacer	0.4	34.9

For both sets of disks a 1-2 dB improvement in SNR is achieved for the laminated media compared to the non-laminated AFC media and the conventional single layer media.

CLAIMS

1. A magnetic recording medium comprising:
a substrate;
a magnetic recording layer (30') on the substrate and comprising first (34') and second (32') antiferromagnetically-coupled (AFC) layers and a nonferromagnetic spacer layer (36') separating the two AFC layers, each AFC layer comprising a first ferromagnetic film (44, 54), a second ferromagnetic film (42, 52) and an antiferromagnetically coupling film (46, 56) located between the first and second films and having a thickness and composition sufficient to provide antiferromagnetic coupling of the first and second films, the nonferromagnetic spacer layer being located between the second film of the first AFC layer and the first film of the second AFC layer and having a thickness and composition sufficient to prevent any significant coupling between the second film of the first AFC layer and the first film of the second AFC layer.

2. A medium as claimed in claim 1 further comprising a third AFC layer and a second nonferromagnetic spacer layer located between the second film (54) of the second AFC layer (32') and the first film of the third AFC layer and having a thickness and composition sufficient to prevent any significant coupling between the second film of the second AFC layer and the first film of the third AFC layer.

3. A medium as claimed in claim 1 wherein the first ferromagnetic film (44) of the first AFC layer (34') has a thickness t1 and a magnetization M1, the second ferromagnetic film (42) of the first AFC layer has a thickness t2 and a magnetization M2, and wherein the magnetic moments per unit area (M1 x t1) and (M2 x t2) of the first and second ferromagnetic films of the first AFC layer, respectively, are different from one another.

4. A medium as claimed in claim 3 wherein the first (44) and second (42) ferromagnetic films of the first AFC layer (32') are formed of the same material, and wherein t1 is different from t2.

5. A medium as claimed in claim 3 wherein the first (44) and second (42) ferromagnetic films of the first AFC layer (32') are formed of different materials and wherein t1 and t2 are substantially the same thickness.

6. A medium as claimed in claim 1 wherein the antiferromagnetically coupling film (46, 56) of one of the AFC layers is formed of a material

selected from the group consisting of ruthenium (Ru), chromium (Cr), rhodium (Rh), iridium (Ir), copper (Cu), and their alloys.

7. A medium as claimed in claim 1 wherein the first (44) and second (42) ferromagnetic films of each of the AFC layers (34', 32') are made of a material selected from the group consisting of Co, Fe, Ni, and their alloys.

8. A medium as claimed in claim 1 wherein the first ferromagnetic film (44, 54) of one of the AFC (34', 32') layers includes an interface film consisting essentially of cobalt located at the interface of the first ferromagnetic film and the antiferromagnetically coupling film (46, 56).

9. A medium as claimed in claim 1 wherein the second ferromagnetic film (42, 52) of one of the AFC layers (34', 32') includes an interface film consisting essentially of cobalt located at the interface of the second ferromagnetic film and the antiferromagnetically coupling film (46, 56).

10. A medium as claimed in claim 1 further comprising an underlayer located on the substrate between the substrate and the magnetic recording layer (30').

11. The medium of claim 1 further comprising a protective overcoat formed over the magnetic recording layer (30').

12. A medium as claimed in claim 1 further comprising:

an underlayer located between the substrate and the magnetic recording layer (30'); and

wherein:

said first (44, 54) and second (42, 52) ferromagnetic films are made of a cobalt alloy; and

said antiferromagnetic coupling film (36') is made of a material selected from the group including ruthenium (Ru), chromium (Cr), rhodium (Rh), iridium (Ir), copper (Cu) and their alloys.

13. A medium as claimed in claim 12 further comprising a third AFC layer and a second nonferromagnetic spacer layer located between the second film (42) of the second AFC layer and the first film of the third AFC layer (32') and having a thickness and composition sufficient to prevent any significant coupling between the second film of the second AFC layer and the first film of the third AFC layer.

14. A medium as claimed in claim 12 wherein the first ferromagnetic film (54) of the first AFC layer (34') has a thickness t1 and a magnetization M1, the second ferromagnetic film (52) of the first AFC layer has a thickness t2 and a magnetization M2, and wherein the magnetic moments per unit area (M1 x t1) and (M2 x t2) of the first and second ferromagnetic films of the first AFC layer, respectively, are different from one another.

15. A medium as claimed in claim 14 wherein the first (54) and second (52) ferromagnetic films of the first AFC layer (34') are formed of the same material, and wherein t1 is different from t2.

16. A medium as claimed in claim 14 wherein the first (54) and second (52) ferromagnetic films of the first AFC layer (34') are formed of different materials and wherein t1 and t2 are substantially the same thickness.

17. A medium as claimed in claim 12 wherein the first ferromagnetic film (54, 44) of one of the AFC layers (34', 32') includes an interface film consisting essentially of cobalt located at the interface of the first ferromagnetic film and the antiferromagnetically coupling film (36').

18. A medium as claimed in claim 12 wherein the second ferromagnetic film (52, 42) of one of the AFC layers (34', 32') includes an interface film consisting essentially of cobalt located at the interface of the second ferromagnetic film and the antiferromagnetically coupling film (36').