"PERPENDICULAR MAGNETIC RECORDING MEDIUM"

The present invention generally relates to perpendicular magnetic recording mediums, and more particularly to a perpendicular magnetic recording medium having satisfactory perpendicular magnetic recording and reproducing characteristics.

Generally, when recording and reproducing a signal on and from a magnetic recording medium by use of a magnetic head, the magnetic head magnetizes a magnetic layer of the magnetic recording medium in a longitudinal direction of the magnetic recording medium (that is, in an in-plane direction) at the time of the recording and picks up the recording at the time of the reproduction. However, according to such a longitudinal magnetic recording system, it is known that the demagnetization field becomes high as the recording density increases and the demagnetization field introduces undesirable effects to the high density magnetic recording. Hence, in order to eliminate the undesirable effects of the demagnetization, a perpendicular magnetic recording system has been proposed in which the magnetic head magnetizes the magnetic layer of the magnetic recording medium in a direction perpendicular to the magnetic layer. According to the perpendicular magnetic recording system, the demagnetization field becomes low as

the magnetic recording density increases, and theoretically, it is possible to realize a satisfactory high density magnetic recording in which there is no decrease in the remanent magnetization.

As a conventional perpendicular magnetic recording medium which is used in the perpendicular magnetic recording system, there is a perpendicular magnetic recording medium having a cobalt-chromium (Co-Cr) film formed on a base film by a sputtering process. As is well known, the Co-Cr film is extremely suited for use in the perpendicular magnetic recording medium because the Co-Cr film has a relatively high saturation magnetization (Ms) and favors magnetization in a direction perpendicular to the Co-Cr film (that is, the coercivity in the direction perpendicular to the Co-Cr film is large and the axis of easy magnetization is perpendicular to the Co-Cr film).

However, due to the addition of chromium (Cr), cobalt (Co) has such an orientation that the axis of easy magnetization thereof is approximately perpendicular to the Co-Cr film but the axis of easy magnetization is not perfectly perpendicular, and it is impossible to obtain an extremely strong perpendicular anisotropic magnetic field with the perpendicular magnetic recording medium comprising the Co-Cr film. Hence, there is another perpendicular magnetic recording medium in which a third element is added

to Co-Cr so that the axis of easy magnetization of Co is satisfactorily perpendicular to the film. For example, niobium (Nb) or tantalum (Ta) is added to Co-Cr as the third element. In this case, due to the addition of Nb or Ta, the orientation of Co is improved so that the axis of easy magnetization is satisfactorily perpendicular to the film but the saturation magnetization of the perpendicular magnetic recording medium decreases by the addition of Cr and Nb (or Ta) which are non-magnetic materials to Co which is a ferromagnetic material. As a result, there is a disadvantage in that it is impossible to obtain a high reproduced output due to the saturation magnetization.

Accordingly, a perpendicular magnetic recording medium having a double film construction has been proposed. According to this perpendicular magnetic recording medium, a film having a high permeability, that is, a film having a low coercivity such as a nickel-iron (Ni-Fe) film, is formed between the Co-Cr film and the base film. The magnetic flux which is spread within the high permeability film is concentrated toward the magnetic pole of the perpendicular magnetic head at a predetermined magnetic recording position in order to obtain a strong magnetization which is in the perpendicular direction and does not spread in the longitudinal direction of the perpendicular magnetic recording medium. However, in the

case of the perpendicular magnetic recording medium having the double film construction, the coercivity of the high permeability film is extremely small compared to the coercivity of the Co-Cr film, and there is a disadvantage in that Barkhausen noise is generated. For example, the coercivity of the Co-Cr film is over 700 Oe, and the coercivity of the high permeability film is under 10 Oe. In order to prevent the generation of the Barkhausen noise, the high permeability film must have a coercivity which is at least over 10 Oe, but there is no suitable material which satisfies such a condition and can also be used for the high permeability film.

Furthermore, when a ring core head is used as the perpendicular magnetic head, there is a problem in that it is impossible to effectively perform the perpendicular magnetic recording with respect to the perpendicular magnetic recording medium described before which has the strong anisotropy only in the perpendicular direction, because a magnetic field generated by the ring core head includes considerable in-plane components.

According to the invention, there is provided a perpendicular magnetic recording medium on which a

signal is recorded and from which the signal is reproduced by a magnetic head, said perpendicular magnetic recording medium comprising:
a recording medium base; and
a magnetic layer constituted by a lower layer formed on the recording medium base and an upper layer formed on the lower layer, said lower layer having an in-plane coercivity between 10 Oe and 220 Oe and a thickness between 0.05 micron and 0.15 micron and being made of a first material including cobalt, chromium and at least one element other than cobalt and chromium with a predetermined range of concentration so that an in-plane M-H hysteresis loop of said magnetic layer has an inclination such that the inclination of a part of the in-plane M-H hysteresis loop in the vicinity of the origin is substantially greater than the inclination of the remaining part of the in-plane M-H hysteresis loop, said upper layer being made of a second material including cobalt, chromium and said at least one element, the concentration of said at least one element in said second material being less than the concentration of said at least one element in said first material.

It is thus possible to provide a perpendicular magnetic recording medium in which the disadvantages and problems of the pior art are overcome, by noting the fact that,

when a magnetic material is coated on a base to form a magnetic layer, the formed magnetic layer is constituted by two layers having different coercivities and utilizing for the perpendicular magnetic recording one of the two layers having a small coercivity.

It is possible to obtain a high reproduced output, and a reproduced output versus recording wavelength characteristic is especially satisfactory in a short recording wavelength range. In addition, an in-plane magnetization (M-H) hysteresis loop of a magnetic layer as a whole rises sharply and anomalously in a vicinity of an origin and the so-called magnetization jump occurs. In other words, the in-plane M-H hysteresis loop has a steep rise in the vicinity of the origin where the in-plane M-H hysteresis loop has an inclination substantially greater than the inclination of the remaining part of the in-plane M-H hysteresis loop. Thus, the perpendicular magnetic recording and reproducing characteristics can be improved by using as the magnetic layer the layer in which the magnetization jump occurs. In the present specification, a sudden change or steep inclination in the in-plane M-H hysteresis loop will be referred to as the magnetization jump, and a magnitude of the magnetization jump will be referred to as a magnetization jump quantity.

The invention will be further described, by way of example, with reference to the accompanying drawings, in which:

FIG. 1 shows an in-plane M-H hysteresis loop for the case where a magnetic layer of an embodiment of the perpendicular magnetic recording medium according to the present invention is constituted by a cobalt-chromium-niobium (Co-Cr-Nb) single film having a thickness of 0.2 micron and a magnetic field of 15 kOe is applied thereto;

FIG. 2 shows an in-plane M-H hysteresis loop for the case where the magnetic layer of the embodiment of the perpendicular magnetic recording medium according to the present invention is constituted by a Co-Cr-Nb single film

having a thickness of 0.05 micron and a magnetic field of 15 kOe is applied thereto;

FIGS.3 through 5 respectively show in-plane M-H hysteresis loops for explaining the reason why a magnetization jump occurs;

FIG.6 is a graph showing an in-plane coercivity Hc(//), a perpendicular coercivity Hc(⊥) and a magnetization jump quantity σ_j for each film thickness when the film thickness of the Co-Cr-Nb single film is controlled by varying the sputtering time;

FIG.7 is a graph showing an in-plane coercivity Hc(//), a perpendicular coercivity Hc(⊥) and a magnetization jump quantity σ_j for each film thickness when the film thickness of a cobalt-chromium-tantalum (Co-Cr-Ta) single film is controlled by varying the sputtering time;

FIGS.8A through 8C are graphs respectively showing an in-plane M-H hysteresis loop of the Co-Cr-Nb single film in which no magnetization jump occurs;

FIG.9 is a graph showing the relationships of the rocking curve half-value ($\Delta\theta_{50}$) of the hcp (002) plane of each of a cobalt-chromium (Co-Cr) thin film and the Co-Cr-Nb single film with respect to the film thickness;

FIGS.10A through 10C are graphs respectively showing torque curves of the Co-Cr thin films respectively having film thicknesses of 0.50, 0.20 and 0.05 micron;

FIGS.11A through 11C are graphs respectively showing torque curves of the Co-Cr-Nb single films respectively having film thicknesses of 0.50, 0.18 and 0.05 micron;

FIG.12 is a graph showing the relationships between the recording wavelength and the reproduced output when the perpendicular magnetic recording and reproduction are performed with respect to each of the recording mediums shown in Table 1 by use of a ring core head;

FIG.13 is a graph showing the relationships between the recording wavelength and the reproduced output when the perpendicular magnetic recording and reproduction are performed with respect to each of the recording mediums shown in Table 2 by use of the ring core head;

FIG.14 is a graph showing an in-plane M-H hysteresis loop of a double film recording medium shown in Table 1;

FIG.15 is a graph showing an in-plane M-H hysteresis loop of a double film recording medium shown in Table 2;

FIG.16 is a diagram for explaining a magnetic loop formed within the double film recording medium by a magnetic flux of the ring core head; and

FIG.17 is a diagram for explaining that lower portions of remanent magnetic fields in a crystal layer of

coarse grain is linked via a crystal layer of fine grain.

The perpendicular magnetic recording medium (hereinafter simply referred to as a recording medium) is made by sputtering on a substrate or a tape which becomes a base first and second magnetic materials which are used as targets. For example, the substrate or tape is made of a polyimide resin or the like, and the first magnetic material sputtered on the base contains cobalt (Co), chromium (Cr) and at least an element such as niobium (Nb) and tantalum (Ta). The second magnetic material sputtered on the layer of the first magnetic material contains Co, Cr and at least an element such as Nb and Ta. A quantity of the element(s) added to Co and Cr in the second magnetic material is smaller than a quantity of the element(s) added to Co and Cr in the first magnetic material. The elements added to Co and Cr in the first and second magnetic materials are not limited to Nb and Ta, and the element(s) added to Co and Cr in the first magnetic material need not be identical to the element(s) added to Co and Cr in the second magnetic material. Furthermore, Nb may be added to Co and Cr in the first magnetic material while Nb and Ta are added to Co and Cr in the second magnetic material, for example.

When a metal or the like such as an Co-Cr alloy is sputtered on the base, it is known that the sputtered

film does not have the same crystal structure in a direction perpendicular to the film surface. It is known from various experiments and from scanning electron microscope (SEM) pictures that a first crystal layer of fine grain is formed in a vicinity of the base for an extremely small thickness, and a second crystal layer of coarse gain is formed on the first crystal layer. For example, the fact that the first crystal layer at the bottom portion of the sputtered film does not have a well defined columnar structure while the second crystal layer formed on the first crystal layer has a well defined columnar structure, is disclosed by Edward R. Wuori and Professor J. H. Judy, "Initial Layer effects in Co-Cr films", IEEE TRANSACTIONS ON MAGNETICS, Vol.MAG-20, No.5, September 1984, pp. 774-775, and by William G. Haines, "VSM Profiling of CoCr Films: A New Analytical Technique", IEEE TRANSACTIONS ON MAGNETICS, Vol.MAG-20, No.5, September 1984, pp. 812-814.

The present inventors noted on the above points, and sputtered on various metals which have a Co-Cr alloy as the base and are respectively added with a third element. Then, physical characteristics of the first crystal layer of fine grain formed on the bottom portion of the sputtered metal film and the second crystal layer of coarse grain formed on the first crystal layer were measured for each of

the various sputtered metal films. As a result, it was found that when Nb or Ta is added to the metal as the third element, the coercivity of the first crystal layer of fine grain is extremely small compared to that of the second crystal layer of coarse grain and there is not a substantial difference between the in-plane coercivity of the first crystal layer and the perpendicular coercivity of the first crystal layer. The present invention is characterized in that this first crystal layer having the small perpendicular coercivity which is not much different from the in-plane coercivity thereof is used as an isotropic layer, namely as a lower layer, and a layer having a large saturation magnetization is formed on the first crystal layer and is used as a perpendicular magnetization layer of the recording medium, namely as an upper layer where the layer having the large saturation magnetization is a thin film such as a Co-Cr-Nb or Co-Cr-Ta thin film having such an orientation that an axis of easy magnetization thereof is in a direction perpendicular to the film.

Description will now be given with respect to the experimental results which were obtained by measuring the coercivities of the first and second crystal layers formed on the base by the sputtering. A Co-Cr-Nb thin film or a Co-Cr-Ta thin film is formed on the base by a sputtering process performed under the following conditions.

(1) Sputtering apparatus:

RF magnetron sputtering apparatus.

(2) Sputtering method:

Continuous sputtering, at an initial discharge pressure of $1x10^{-6}$ Torr and introducing argon (Ar) gas until the pressure reaches $1x10^{-3}$ Torr.

(3) Base:

A polyimide resin having a thickness of 20 microns.

(4) Target:

A composite target obtained by placing small pieces of Nb or Ta on the Co-Cr alloy.

(5) Distance between target and base:

110 mm.

The magnetic characteristic of the thin films was measured by a vibrating sample magnetometer manufactured by Riken Denshi of Japan, the composition of the thin films was measured by an energy dispersion type microanalyzer manufactured by KEVEX of the United States and the crystal orientation of the thin films was measured by an X-ray analyzer manufactured by Rigaku Denki of Japan.

FIG.1 shows an in-plane M-H hysteresis loop for the case where a magnetic field of 15 kOe is applied to a recording medium which is obtained by adding Nb to Co-Cr as the third element (the same phenomenon occurs when the Nb

is added in a range of 2 to 10 at%) and sputtering the Co-Cr-Nb single film on the polyimide resin base with a film thickness of 0.2 micron. As shown in FIG.1, the in-plane M-H hysteresis loop rises sharply and anomalously in a vicinity of an origin as indicated by an arrow A and the so-called magnetization jump (hereinafter simply referred to as a jump) occurs. When it is assumed that a uniform crystal growth constantly occurs when the Co-Cr-Nb is sputtered on the base to form the Co-Cr-Nb thin film, the jump shown in FIG.1 would not occur, and it can therefore be conjectured that a plurality of crystal layers having different magnetic characteristics coexist within the Co-Cr-Nb thin film.

FIG.2 shows an in-plane M-H hysteresis loop for the case where a magnetic field of 15 kOe is applied to a recording medium which is obtained by sputtering the Co-Cr-Nb on the polyimide resin base with a film thickness of 0.05 micron under the same sputtering condition. Unlike the case shown in FIG.1, there is no jump in the in-plane M-H hysteresis loop shown in FIG.2, and it can be seen that the Co-Cr-Nb thin film having a film thickness in the order of 0.05 micron is constituted by a substantially uniform crystal layer. In addition, it can be seen from FIG.2 that an in-plane coercivity Hc(//) (hereinafter simply referred to as a coercivity Hc(//)) for the case where the film

thickness is in the order of 0.05 micron is extremely small and the in-plane permeability is therefore extremely high. From these results, the coercivity Hc(//) of an initial layer which initially grows in the vicinity of the base by the sputtering is small, and this initial layer can be regarded as the first crystal layer of fine grain (hereinafter simply referred to as the first crystal layer) which has been confirmed by the SEM pictures as described before. A layer which grows on the initial layer has a coercivity Hc(//) which is larger than the coercivity Hc(//) of the initial layer, and this layer can be regarded as the second crystal layer of coarse grain (hereinafter simply referred to as the second crystal layer) which has also been confirmed by the SEM pictures.

The reason why the jump occurs in the Co-Cr-Nb single film in which the first and second crystal layers coexist will now be described in conjunction with FIGS.3 through 5. It should be noted that the jump does not occur for all Co-Cr-Nb thin films with different compositions and sputtering conditions, as will be described later on in the specification. When the Co-Cr-Nb thin film is formed under a predetermined sputtering condition and the in-plane M-H hysteresis loop is obtained for this thin film by measurement, the obtained in-plane M-H hysteresis loop rises sharply in a vicinity of an origin as shown in FIG.3

and the jump occurs. An in-plane M-H hysteresis loop shown in FIG.4 for a thin film solely consisting of the first crystal layer can be obtained by measurement by forming a thin film which has a small film thickness. The second crystal layer can be regarded as having a uniform crystal structure, and further, the in-plane M-H hysteresis loop shown in FIG.3 can be regarded as a composition of the in-plane M-H hysteresis loop of the first crystal layer and an in-plane M-H hysteresis loop of the second crystal layer. Hence, the in-plane M-H hysteresis loop of the second crystal layer can be regarded as a smooth hysteresis loop shown in FIG.5 in which the coercivity Hc(//) is larger than that of the first crystal layer and no jump occurs. In other words, the existence of the jump in FIG.3 indicates that two layers having different magnetic characteristics coexist in the same single film. For this reason, it can be understood that two layers having different magnetic characteristics also coexist in the Co-Cr-Nb single film having the in-plane M-H hysteresis loop shown in FIG.1. The coercivity of the second crystal layer can be obtained from a hysteresis loop which is obtained by subtracting the in-plane M-H hysteresis loop of the Co-Cr-Nb thin film which solely consists of the first crystal layer from the in-plane M-H hysteresis loop of the Co-Cr-Nb thin film in which the first and second crystal

layers coexist. From the experimental results, it is proved that two layers having different magnetic characteristics coexist in the Co-Cr-Nb single film when the in-plane M-H hysteresis loop of the Co-Cr-Nb thin film has a sharp rise in the vicinity of the origin and the jump occurs.

Next, description will be given with respect to the magnetic characteristics of the two layers constituting the Co-Cr-Nb single film which is sputtered on the base in relation to the film thickness of the Co-Cr-Nb thin film, by referring to FIG.6. FIG.6 is a graph showing the coercivity Hc(//), a perpendicular coercivity Hc($\perp$) (hereinafter simply referred to as a coercivity Hc($\perp$)) and a magnetization jump quantity (hereinafter simply referred to as a jump quantity) σ_j for each film thickness when the film thickness of the Co-Cr-Nb thin film is controlled by varying the sputtering time.

Giving attention to the coercivity Hc(//), the coercivity Hc(//) is under 180 Oe and is extremely small when the film thickness is under 0.15 micron, and the in-plane permeability can be regarded as being high. Further, a difference in the values of the coercivities Hc($\perp$) and Hc(//) in a vicinity of the film thickness at which the jump occurs is relatively small, and it can be said that the Co-Cr-Nb thin film is an isotropic layer. In

addition, the coercivity Hc(//) does not change greatly even when the film thickness increases. On the other hand, giving attention to the jump quantity σ_j, the jump quantity σ_j rises sharply at the film thickness of substantially 0.075 micron and describes an upwardly-opening parabola for the thickness of over 0.075 micron. Further, giving attention to the coercivity Hc(⊥), the coercivity Hc(⊥) rises sharply from substantially 180 Oe at the film thickness of 0.05 to 0.15 micron and is over 900 Oe for the film thickness of over 0.15 micron. From these results, it can be seen that a boundary between the first and second crystal layers exists at the film thickness of approximately 0.05 to 0.15 micron. The coercivities Hc(//) and Hc(⊥) of the first crystal layer are both under 180 Oe and small, and the first crystal layer is an isotropic layer in which the difference between the coercivities Hc(//) and Hc(⊥) is small. At such a film thickness that the jump does not occur, the coercivities Hc(//) and Hc(⊥) are both under 180 Oe and small. But at such a large film thickness that the jump occurs, the coercivity Hc(⊥) sharply increases. It is hence also seen from this point of view that the Co-Cr-Nb single film is constituted by two layers having different magnetic characteristics when the jump occurs. According to the experiments performed by the present inventors, when the composition and/or the

sputtering condition is slightly changed, there is a slight change in the film thickness at which the jump quantity σ_j and the coercivity Hc(⊥) respectively rise sharply, and the slight change in the film thickness occurs within the range of 0.05 to 0.15 micron. In addition, there are slight changes in the coercivities Hc(//) and Hc(⊥) when the above conditions are changed, and the value of the coercivity Hc(//) changes in the range of between substantially 10 and substantially 220 Oe. That is, it can be regarded that the jump occurs when the first crystal layer has a thickness in the range of 0.05 to 0.15 micron and the coercivity Hc(//) is in the range of between substantially 10 and substantially 220 Oe.

Next, the results shown in FIG.7 are obtained when similar experiments are performed by adding Ta to Co-Cr as the third element (the same phenomenon occurs when the Ta is added in a range of 2 to 10 at%) and sputtering the Co-Cr-Ta on the polyimide resin base with various film thicknesses. FIG.7 is a graph showing the coercivity Hc(//), the perpendicular coercivity Hc(⊥) and the jump quantity σ_j for each film thickness when the film thickness of the Co-Cr-Ta single film is controlled by varying the sputtering time. The results obtained by adding the Ta to the Co-Cr are similar to the case where the Nb is added to the Co-Cr. As shown in FIG.7, the boundary between the first and second crystal layers exists at the film

thickness of 0.05 to 0.15 micron. The coercivities Hc(//) and Hc(⊥) of the first crystal layer are both under 170 Oe and small, and the first crystal layer is an isotropic layer in which the difference between the coercivities Hc(//) and Hc(⊥) is small.

It should be noted from the experiments described above that the jump does not occur when the sputtering condition and the adding quantity of the Nb or Ta (2 to 10 at% in the case of the Nb and 1 to 10 at% in the case of the Ta) are changed from those described before, however, the first and second crystal layers are also formed within the Co-Cr-Nb singlefilm, the Co-Cr-Ta singlefilm and the Co-Cr single film in which no jump occurs (refer to the references cited on page 9). An example of the in-plane M-H hysteresis loop of the Co-Cr-Nb single film in which no jump occurs will be described by referring to FIGS.8A through 8C. FIG.8A shows the in-plane M-H hysteresis loop for both the first and second crystal layers, FIG.8B shows the in-plane M-H hysteresis loop solely for the first crystal layer and FIG.8C shows the in-plane M-H hysteresis loop solely for the second crystal layer. It is seen from FIGS.8A through 8C that the in-plane remanent magnetization Mr_B(//) of the first crystal layer is larger than the in-plane remanent magnetization Mr_C of the second crystal layer. Further, the in-plane remanent magnetization

Mr_A(//) of both the first and second crystal layers is unfavorable compared to the in-plane remanent magnetization Mr_C(//) of the second crystal layer, and the anisotropic magnetic field Hk is small. In addition, it is known that the orientation of the first crystal layer is poor (the $\Delta\theta_{50}$ is large) and the first crystal layer is unsuited for the perpendicular magnetic recording.

FIG.9 is a graph showing the relationships of the rocking curve half-value ($\Delta\theta_{50}$) of the hcp (002) plane of each of a cobalt-chromium (Co-Cr) single film (composition of $Co_{81}Cr_{19}$ at%) and the Co-Cr-Nb single film with respect to the film thickness. The Co-Cr thin film is formed under the same sputtering conditions as those described before except for the condition (4), and the Co-Cr alloy alone is used as the target in this case. It is seen from FIG.9 that the orientation of the Co-Cr-Nb thin film is extremely poor in the initial stage of the film formation while the orientation of the Co-Cr thin film is satisfactory in the initial stage of the film formation. However, the orientation of the Co-Cr-Nb thin film improves rapidly as the film thickness of the thin film increases. In other words, the orientation of the Co-Cr-Nb thin film is poor in the initial stage of the film formation, that is, during the formation of the first crystal layer, but the orientation of the Co-Cr-Nb thin film rapidly improves when

the film thickness becomes over substantially 0.15 micron, that is, when the second crystal layer is formed. Hence, it can be understood that in the case of the Co-Cr-Nb thin film, two layers having different magnetic characteristics are formed depending on the film thickness, and the orientation of the second crystal layer is more satisfactory than that of the Co-Cr thin film.

Next, the Co-Cr-Nb thin film will be examined from the point of view of the magnetic anisotropy. FIGS.10A through 10C are graphs respectively showing torque curves of the Co-Cr single films respectively having film thicknesses of 0.50, 0.20 and 0.05 micron, and FIGS.11A through 11C are graphs respectively showing torque curves of the Co-Cr-Nb single films respectively having film thicknesses of 0.50, 0.18 and 0.05 micron. In each of these graphs, the abscissa (θ) represents the angle formed between the normal to the film surface and the applied magnetic field, the ordinate represents the torque, and the applied magnetic field to the thin film is 10 kOe. Moreover, the Co-Cr thin films and the Co-Cr-Nb thin films respectively have the composition of $Co_{81}Cr_{19}$ at% and $Co_{77.9}Cr_{16.0}Nb_{6.1}$ at% and the saturation magnetization Ms of 400 emu/cc and 350 emu/cc.

In the case of the Co-Cr thin films shown in FIGS.10A through 10C, the polarity of the torque curve is

the same for the three thin films and the axis of easy magnetization is perpendicular to the film surface. In the case of the Co-Cr-Nb thin films shown in FIGS.11A and 11B respectively having the film thicknesses of 0.50 and 0.18 micron, the polarity of the torque curve is the same for the two thin films and the axis of easy magnetization is perpendicular to the film surface. However, in the case of the Co-Cr-Nb thin film shown in FIG.11C having the film thickness of 0.05 micron, the polarity of the torque curve is opposite to that of the torque curves of the other thin films and the axis of easy magnetization is in-plane of the thin film. As described before, it can be regarded that only the first crystal layer is formed in the case of the Co-Cr-Nb thin film having the film thickness of 0.05 micron, and the axis of easy magnetization of the first crystal layer is in-plane of the first crystal layer. Further, it should be noted that in the torque curves of the Co-Cr-Nb thin films having the film thicknesses of over 0.05 micron, there are anomalous parts indicated by arrows B in FIGS.11A and 11B. It can be regarded that the anomalous part in the torque curve is introduced due to the magnetic characteristic of the first crystal layer. In other words, when the film thickness of the thin film becomes larger than a predetermined value, the second crystal layer which has an axis of easy magnetization

perpendicular to the film surface is formed on the first crystal layer which has an axis of easy magnetization in-plane of the first crystal layer. It can be conjectured that the first and second crystal layers having the different magnetic characteristics affect each other and the anomalous part is introduced in the torque curve of the thin film as a whole. It is hence also proved from the torque curves that two layers having different magnetic characteristics coexist in the single Co-Cr-Nb thin film.

When the Co-Cr-Nb or Co-Cr-Ta single film constituted by the first and second crystal layers is used as the magnetic layer of the perpendicular magnetic recording medium and an attempt is made to magnetize the entire thin film in the direction perpendicular to the film surface according to the conventional concept, it was conventionally considered that the existence of the first crystal layer is an extremely unfavorable primary factor to the perpendicular magnetization. The existence of the first crystal layer was considered to be an unfavorable primary factor for both cases where the jump does and does not occur. In other words, in the case where the jump occurs, the coercivities Hc(//) and Hc(⊥) of the first crystal layer is extremely small and it can be regarded that there is virtually no perpendicular magnetization in the first crystal layer. On the other hand, in the case

where the jump does not occur, the coercivity Hc(//) of the first crystal layer is larger than that of the case where the jump occurs, but the coercivity Hc(⊥) of the first crystal layer is insufficient for realizing the perpendicular magnetic recording, and it can be regarded that it is impossible to perform a satisfactory perpendicular magnetic recording. Accordingly, even when the magnetization is performed in the direction perpendicular to the film surface, there is virtually no perpendicular magnetization in the first crystal layer, and the efficiency of the perpendicular magnetization of the thin film as a whole is deteriorated. Such a deterioration in the efficiency of the perpendicular magnetization is especially notable in the case of a magnetic head such as the ring core head which generates a magnetic field including considerable components in the in-plane direction.

However, the first crystal layer of the recording medium according to the present invention has such a characteristic that the coercivity Hc(//) is small, that is, the first crystal layer has a relatively high permeability and an isotropic magnetic characteristic. The characteristic of the first crystal layer is thus similar to the high permeability layer of the conventional recording medium provided between the Co-Cr film and the

base. It can thus be regarded that in the Co-Cr-Nb or Co-Cr-Ta single film, the first crystal layer having the low coercivity Hc(//) is usable as the high permeability layer of the recording medium.

Accordingly, it is possible to consider utilizing the first crystal layer as the high permeability layer when sputtering the single layer of the Co-Cr-Nb or Co-Cr-Ta thin film and utilizing the second crystal layer as the perpendicular magnetization layer. However, in the single layer of the Co-Cr-Nb or Co-Cr-Ta thin film, the quantity of Nb or Ta added to Co-Cr becomes limited to a predetermined quantity with which the jump occurs. In addition, when Nb or Ta which is a non-magnetic material is added to Co which is a ferromagnetic material, the saturation magnetization Ms becomes small compared to that of the Co-Cr thin film, and it is impossible to perform perpendicular magnetic recording and reproduction so that a high reproduced output is obtainable.

By taking the above points into consideration, the recording medium according to the present invention is formed as follows. That is, a first crystal layer of fine grain of a Co-Cr-Nb or Co-Cr-Ta thin film is formed on a base under the conditions with which the jump described before would occur if the thickness of the lower crystal layer were over a predetermined value, and then, an upper

layer of a Co-Cr-Nb or Co-Cr-Ta thin film having a high saturation magnetization Ms and having such an added quantity of Nb or Ta that is smaller than an added quantity with which the jump would occur is formed on the lower crystal layer. The upper layer is used as a layer which contributes to the perpendicular magnetic recording and reproduction.

Table 1 shows various magnetic characteristics of a single film recording medium I comprising a single thin film of Co-Cr-Nb in which the jump occurs, a single film recording medium II comprising a single thin film of Co-Cr-Nb in which the added quantity of Nb is small and the jump does not occur, and a double film recording medium III having the construction described above wherein the lower crystal layer is constituted by a Co-Cr-Nb thin film which is formed under such conditions that the jump would occur if the thickness of the lower crystal layer were over a predetermined value and the upper layer is constituted by a Co-Cr-Nb thin film which is formed under such conditions that the jump would not occur even if the thickness of upper crystal layer were over a predetermined value. In the double film recording medium III, the added quantity of Nb in the upper layer is smaller than the added quantity of Nb in the lower crystal layer. The relationships between the recording

wavelength and the reproduced output when the perpendicular magnetic recording and reproduction are performed with respect to each of the recording mediums shown in Table 1 by use of a ring core head made of sendust (registered trademark) are shown in FIG.12.

Table 2 shows various magnetic characteristics of a single film recording medium IV comprising a single thin film of Co-Cr-Ta in which the jump occurs, a single film recording medium V comprising a single thin film of Co-Cr-Ta in which the added quantity of Ta is small and the jump does not occur, and a double film recording medium VI having the construction described above wherein the lower crystal layer is constituted by a Co-Cr-Ta thin film which is formed under such conditions that the jump would occur if the thickness of the lower crystal layer were over a predetermined value and the upper layer is constituted by a Co-Cr-Ta thin film which is formed under such conditions that the jump would not occur even if the thickness of the upper layer were over a predetermined value. In the double film recording medium VI, the added quantity of Ta in the upper layer is smaller than the added quantity of Ta in the lower crystal layer. The relationships between the recording wavelength and the reproduced output when the perpendicular magnetic recording and reproduction are performed with respect to

each of the recording mediums shown in Table 2 by use of the ring core head made of sendust (registered trademark) are shown in FIG.13.

In Tables 1 and 2, U and L respectively represent upper and lower layers of the double film recording medium, δ represents the film thickness, Ms represents the saturation magnetization, Hc($\perp$) represents the perpendicular coercivity, Hc(//) represents the in-plane coercivity, Mr(//)/Ms represents the in-plane squareness ratio, Mr(//) represents the in-plane remanent magnetization, $\Delta\theta_{50}$ represents the rocking half-value of the hcp (002) plane, and "YES" and "NO" under the column "Jump" indicates whether or not the jump occurs. In FIGS.12 and 13, the same designations used in Tables 1 and 2 are used to indicate the respective reproduced output versus recording wavelength characteristics of the recording mediums I through VI.

Table 1

	Composition (at%)		δ (μm)	Ms (emu/cc)	Hc(⊥) (Oe)	Hc(//) (Oe)	Mr(//)/Ms	Δθ50 (deg)	Jump
I	$Co_{84.1}Cr_{13.2}Nb_{2.7}$		0.19	448	893	177	0.24	8.7	Yes
II	$Co_{83.0}Cr_{16.7}Nb_{0.3}$		0.19	518	720	460	0.18	8.8	No
III	U	$Co_{83.0}Cr_{16.7}Nb_{0.3}$	0.11	503	816	219	0.21	8.3	Yes
	L	$Co_{84.1}Cr_{13.2}Nb_{2.7}$	0.11					---	

Table 2

	Composition (at%)		δ (μm)	Ms (emu/cc)	Hc(⊥) (Oe)	Hc(//) (Oe)	Mr(//)/Ms	Δθ50 (deg)	Jump
IV	$Co_{84.8}Cr_{13.9}Ta_{1.3}$		0.20	464	1275	231	0.23	8.4	Yes
V	$Co_{83.0}Cr_{16.7}Ta_{0.3}$		0.19	520	1080	570	0.22	9.1	No
VI	U	$Co_{83.0}Cr_{16.7}Ta_{0.3}$	0.09	477	1080	122	0.28	---	Yes
	L	$Co_{84.8}Cr_{13.9}Ta_{1.3}$	0.11					---	

As may be seen from Table 1, the saturation magnetization Ms of the double film recording medium III is greater than the saturation magnetization Ms of the single film recording medium I comprising the Co-Cr-Nb thin film in which the jump occurs. Similarly, the saturation magnetization Ms of the double film recording medium VI is greater than the saturation magnetization Ms of the single film recording medium IV comprising the Co-Cr-Ta thin film in which the jump occurs. In addition, the coercivities Hc(⊥) of the double film recording mediums III and VI are sufficiently high, and the magnetic characteristics of the

double film recording mediums III and VI are suited for the perpendicular magnetic recording and reproduction.

According to the experiments performed by the present inventors, the in-plane squareness ratios Mr(//)/Ms of the double film recording mediums formed under the predetermined conditions described before had a value equal to or greater than a minimum value of 0.21.

On the other hand, as may be seen from the reproduced output versus recording wavelength characteristics shown in FIG.12, the reproduced output obtained with the double film recording medium III is higher than the reproduced outputs obtained with the single film recording mediums I and II for the entire recording wavelength range. Especially in the short recording wavelength range of 1 to 0.2 micron, the reproduced outputs obtained with the single film recording mediums I and II increase, but the reproduced output obtained with the double film recording medium III increases with a much greater rate. Accordingly, it can be seen that the double film recording medium III is especially suited for the perpendicular magnetic recording and reproduction in the short recording wavelength range.

Results similar to those shown in FIG.12 were also obtained with the double film recording medium VI as shown in FIG.13.

FIGS.14 and 15 respectively show the in-plane M-H hysteresis loops of the double film recording mediums III and VI shown in Tables 1 and 2 for the case where a magnetic field of 15 kOe is applied to the double film recording mediums III and VI. As may be seen from FIGS.14 and 15, the in-plane M-H hysteresis loops of the double film recording mediums III and VI respectively have a steep rise in a vicinity of an origin and the so-called jump occurs. The jump quantity of the double film recording medium III is greater than the jump quantity of the single film recording medium I having the in-plane M-H hysteresis loop shown in FIG.1. Similarly, the jump quantity of the double film recording medium VI is greater than the jump quantity of the single film recording medium IV. In other words, the in-plane M-H hysteresis loops of the double film recording mediums III and VI respectively have a steep rise in the vicinity of the origin compared to the in-plane M-H hysteresis loops of the other single film recording mediums, and as may be seen from FIGS.12 and 13, the perpendicular magnetic recording and reproducing characteristics of these recording mediums III and VI are highly efficient compared to those of the single film recording mediums.

The reasons why the phenomenon described before occur will now be described in conjunction with FIG.16.

When Co-Cr-Nb or Co-Cr-Ta (hereinafter simply referred to as Co-Cr-Nb(Ta)) is sputtered on a base 11 made of polyimide resin or the like to a film thickness of substantially 0.1 micron under the conditions with which the jump would occur if the Co-Cr-Nb(Ta) were sputtered to a film thickness over a predetermined value, it can be regarded that a crystal layer 12 of fine grain is formed throughout approximately the entire Co-Cr-Nb(Ta) thin film. The coercivity Hc(//) of this crystal layer 12 is small. For this reason, it is possible to utilize the crystal layer 12 as the so-called high permeability layer of the recording medium so that the crystal layer 12 functions similarly to the high permeability layer.

Co-Cr-Nb(Ta) having an added quantity of Nb(Ta) which is smaller than an added quantity of Nb(Ta) in the crystal layer 12 is sputtered on the crystal layer 12 to a film thickness of substantially 0.1 micron so as to form a crystal layer 13 of coarse grain. The added quantity of Nb(Ta) in the crystal layer 13 is smaller than the added quantity with which the jump would occur if the Co-Cr-Nb(Ta) were sputtered to a film thickness over a predetermined value. When Co-Cr-Nb(Ta) containing less added quantity of Nb(Ta) than Co-Cr-Nb(Ta) forming the crystal layer 12 is sputtered on the crystal layer 12, a crystal layer of fine grain of Co-Cr-Nb(Ta) containing the

less added quantity of Nb(Ta) is essentially not formed at a boundary between Co-Cr-Nb(Ta) forming the crystal layer 12 and Co-Cr-Nb(Ta) forming the crystal layer 13 because the two Co-Cr-Nb(Ta) forming the crystal layers 12 and 13 are similar both in composition and crystal structure. Even if the crystal layer of fine grain of Co-Cr-Nb(Ta) containing the less added quantity of Nb(Ta) should be formed at the boundary, it can be regarded that this crystal layer will not reach such a film thickness that would affect the perpendicular magnetic recording and reproducing characteristics. Hence, it can be regarded that the crystal layer 13 of coarse grain of Co-Cr-Nb(Ta) is formed directly on the crystal layer 12 of fine grain of Co-Cr-Nb(Ta). As described before, the crystal layer 13 has a high saturation magnetization Ms and also has a high coercivity Hc(⊥).

In addition, in Co-Cr-Nb(Ta) which forms the crystal layer 13, the added quantity of Nb(Ta) may be selected arbitrarily without being limited by the conditions with which the jump would occur if the crystal layer 13 were formed to a film thickness over a predetermined value. As described before, the saturation magnetization Ms of Co decreases due to the addition of Nb(Ta), but the axis of easy magnetization of Co is satisfactorily perpendicular to the film. Accordingly, by

appropriately selecting the added quantity of Nb(Ta) to Co and Cr, it is possible to make the Co have such an orientation that the axis of easy magnetization is satisfactorily perpendicular while maintaining a high saturation magnetization Ms.

Accordingly, when a perpendicular magnetic recording is performed with respect to a double film recording medium 14 by use of a ring core head 15, the lines of magnetic flux from the ring core head 15 penetrates the crystal layer 13 and reaches the crystal layer 12. It can be regarded that the lines of magnetic flux advance in the in-plane direction within the crystal layer 12 which is an isotropic low coercivity layer, and then advances perpendicularly toward the magnetic pole portion of the ring core head 15 via the crystal layer 13, to magnetize the crystal layer 13 in the perpendicular direction. Thus, a magnetic loop formed by the magnetic flux has a substantially U-shape as shown in FIG.16. According to this perpendicular magnetic recording, a large remanent magnetization remains within the crystal layer 13 since the magnetic flux is concentrated at a predetermined position where the perpendicular magnetization is performed and perpendicularly penetrates the crystal layer 13 having the large saturation magnetization Ms. In other words, although the magnetic field generated by the ring core head

15 includes considerable in-plane components, it is possible to perform the perpendicular magnetic recording so that the remanent magnetization is large, and it is thus possible to improve the efficiency of the perpendicular magnetic recording and reproduction.

On the other hand, it is known that it is possible to adjust the thermal expansion coefficient of the recording medium by adding one or more elements (that is, Nb and/or Ta, for example) to Co-Cr. Hence, it is possible to adjust the thermal expansion coefficient of the recording medium according to the present invention since the added quantity of the one or more elements added to Co-Cr can be appropriately selected as described above, and it is possible to easily manufacture recording mediums having no curls.

In addition, since the coercivity Hc(//) of the crystal layer 12 is not extremely small compared to the coercivity Hc($\perp$) of the crystal layer 13 as may be seen from FIGS.6 and 7, the Barkhausen noise will not be generated, and it is possible to perform satisfactory perpendicular magnetic recording and reproduction. Furthermore, because the coercivity Hc(//) of the crystal layer 12 is not zero but is in the range of 10 to 220 Oe, it is possible to perform a magnetization corresponding to this coercivity Hc(//).

When the perpendicular magnetic recording is performed with respect to the double film recording medium 14, a plurality of magnets having reversed magnetization direction in correspondence with a predetermined bit interval are alternately formed in the crystal layer 13 as shown in FIG.17, wherein the arrows indicate the directions of the magnetization. Because the crystal layer 12 has a coercivity in the range of 10 to 220 Oe, a magnetic flux linking the lower portions of the mutually adjacent magnets is formed in the crystal layer 12 as indicated by the arrows in FIG.17. Hence, there is no demagnetization phenomenon between the mutually adjacent magnets in the crystal layer 13 because the mutually adjacent magnets are magnetically coupled to each other, and this phenomenon is especially notable when the density between the mutually adjacent magnets is high. As a result, it is possible to obtain a high reproduced output.

On the other hand, it is possible to make the thickness of the recording medium 14 extremely small since the film thickness of the crystal layer 12 is in the order of 0.15 micron and extremely small. As a result, the resiliency of the magnetic layer of the recording medium 14 is very satisfactory, and it is possible to realize a satisfactory contact between the ring core head 15 and the recording medium 14 (that is, the crystal layer 13).

Moreover, the sputtering time required to form the recording medium 14 is short because of the extremely small thickness of the recording medium 14, and the recording medium 14 can be manufactured with a high productivity and at a low cost.

The recording medium of the present invention is not limited to the embodiment described heretofore, and more than one element may be added to Co and Cr in each of the upper and lower layers formed on the base. However, a quantity of the element(s) added to Co and Cr in the upper layer must be smaller than a quantity of the element(s) added to Co and Cr in the lower layer. The elements added to Co and Cr in the materials constituting the upper and lower layers are not limited to Nb and Ta, and the element(s) added to Co and Cr in the lower layer need not be identical to the element(s) added to Co and Cr in the upper layer. In addition, Nb may be added to Co and Cr in the lower layer while Nb and Ta are added to Co and Cr in the upper layer, for example.



CLAIMS

1. 1. A perpendicular magnetic recording medium on which a signal is recorded and from which the signal is reproduced by a magnetic head, said perpendicular magnetic recording medium comprising:

a recording medium base; and

a magnetic layer constituted by a lower layer formed on the recording medium base and an upper layer formed on the lower layer,

said lower layer having an in-plane coercivity between 10 Oe and 220 Oe and a thickness between 0.05 micron and 0.15 micron and being made of a first material including cobalt, chromium and at least one element other than cobalt and chromium with a predetermined range of concentration so that an in-plane M-H hysteresis loop of said magnetic layer has an inclination such that the inclination of a part of the in-plane M-H hysteresis loop in the vicinity of the origin is substantially greater than the inclination of the remaining part of the in-plane M-H hysteresis loop, said upper layer being made of a second material including cobalt, chromium and said at least one element, the concentration of said at least one element in said second material being less than the concentration of said at least one element in said first material.

2. A perpendicular magnetic recording medium as claimed in claim 1, in which said at least one element is one of niobium and tantalum.

3. A perpendicular magnetic recording medium as claimed in claim 2, in which said first material includes cobalt, chromium and niobium which has a concentration in a range between 2 and 10 at %.

* C L M S *

4. A perpendicular magnetic recording medium as claimed in claim 2, in which said first material includes cobalt, chromium and tantalum which has a concentration in a range between 1 and 10 at %.

5. A perpendicular magnetic recording medium as claimed in claim 1, in which in-plane squareness ratio of an in-plane M-H hysteresis characteristic of said upper and lower layers as a whole is 0.21 or more.