

Substrate for a perpendicular magnetic recording medium, a perpendicular magnetic recording medium, and manufacturing methods therefor

5 Technical field of the invention

The present invention relates to a perpendicular magnetic recording medium mounted on various magnetic recording apparatuses including an external storage device of a computer, particularly, a fixed magnetic disk device (hard disk drive), and to a
10 method for manufacturing such a medium. The invention also relates to a substrate for the perpendicular magnetic recording medium, and to a method for manufacturing such a substrate.

Background of the invention

15 A perpendicular magnetic recording system is drawing attention as a technology for achieving high density in magnetic recording to substitute for a conventional longitudinal magnetic recording system. A double layer perpendicular magnetic recording medium, in particular, is known as a perpendicular magnetic recording medium
20 suited for providing high density recording. (See Japanese Patent Publication No. S58-91) The double layer perpendicular magnetic recording medium is provided with a soft magnetic film called a soft magnetic backing layer under a magnetic recording layer, which serves to record information. The backing layer facilitates to pass the

magnetic flux generated by a magnetic head and has high saturation magnetic flux density B_s . The double layer perpendicular magnetic recording medium enhances magnetic field intensity and magnetic field gradient generated by a magnetic head, improves resolution of records, and increases leakage flux from the recording medium.

The soft magnetic backing layer is generally composed of an alloy film of Ni-Fe, or Fe-Si-Al, or an amorphous alloy film of mainly cobalt, formed by a sputtering method and having a thickness in a range of 200 nm to 500 nm. However, forming such a relatively thick film by a sputtering method is unfavorable from the viewpoint of production cost and mass productivity.

To solve this problem, a soft magnetic backing layer is proposed that is formed of a soft magnetic film by an electroless plating method. Feasibility of a soft magnetic backing layer is suggested with the proposed materials of Co-B film (See Japanese Unexamined Patent Application Publication No. H5-1384) and Ni-Fe-P film (See Japanese Unexamined Patent Application Publication No. H7-66034).

In a magnetic recording medium in a longitudinal magnetic recording system for a practically used hard disk drive, a nonmagnetic substrate is provided with a nonmagnetic Ni-P plating film that contains phosphorus in a concentration around 11 wt%, that

has a thickness of 8 μm to 15 μm , and that is formed on an aluminum alloy base by an electroless plating method. The nonmagnetic Ni-P plating film mainly serves to fill in the defects like depressions on the aluminum alloy base as well as to obtain a smooth surface by

5 polishing the surface of the plating film. Further, the nonmagnetic Ni-P plating film is used to secure hardness of the surface required for a substrate of a hard disk. A certain degree of surface hardness is required to prevent the substrate from damage in an event of collision of the magnetic recording medium with the magnetic head during
10 operation of a hard disk drive.

Since the nonmagnetic Ni-P plating film can be made ferromagnetic by heating at a temperature higher than or equal to about 300°C, a proposal has been made to use the Ni-P plating film as
15 a soft magnetic backing layer of a perpendicular magnetic recording medium. It has been proposed (see Japanese Unexamined Patent Application Publication No. H1-285022) to form a soft magnetic Ni-P film by heat-treating a nonmagnetic Ni-P plating film at a temperature higher than or equal to 300°C for use as a soft magnetic
20 backing layer. It has been also proposed (see Japanese Unexamined Patent Application Publication No. H10-228620) that by laminating a soft magnetic Ni-P film that is obtained by heat-treating a nonmagnetic Ni-P plating film at a temperature between 250°C and 500°C and a Sendust film that is formed by sputtering, the Ni-P film

helps the Sendust film exhibit its own function, to attain an effective soft magnetic backing layer.

The nonmagnetic Ni-P plating film has already been practically
5 applied to a nonmagnetic substrate of a hard disk as described above,
thus, mass production methods and the surface smoothing technique
by polishing are well known. Accordingly, the Ni-P plating film is
very promising from the viewpoint of manufacturing cost if the
10 plating film could be transformed to a soft magnetic backing layer by
heat-treatment and could be served for a substrate of a perpendicular
magnetic recording medium.

Problem to be solved by the invention

To use the previously described Co-B plating film or Ni-Fe-P
15 plating film for a soft magnetic backing layer, the surface needs to be
smoothed by polishing. Because the hardness and workability of
these materials are foreseen to be substantially different from those
of the nonmagnetic Ni-P plating film, the conventional processing
technique for the nonmagnetic Ni-P plating film cannot be applied to
20 processing of those materials.

For the materials, such as Ni-Fe, Co-Fe, or other alloys of two or
more component metals, it is very difficult to control, for example, the
composition of the plating bath in an electroless plating method, and

thus the quality of such a material is hardly controlled and maintained in mass production.

The inventors of the present invention made extensive studies on the transformation of the nonmagnetic Ni-P plating film to a soft magnetic state by heat-treatment and found that the Ni-P plating film cannot be sufficiently transformed to soft magnetic state by heat-treatment at a temperature below or equal to 300°C, and heat-treatment at a temperature higher than 300°C, which is necessary to attain soft magnetic state, causes increase in surface roughness of the surface of the plating film. While a commonly used nonmagnetic Ni-P plating film has a homogeneous amorphous structure, the heat-treatment for transformation to a soft magnetic state causes to form both types of crystals of metallic Ni and intermetallic compound of Ni₃P. This structural change can be the reason for the increase in the surface roughness. The increase in the surface roughness disturbs lowering of the magnetic head's flying height; the lowering is essential to high density recording of a hard disk. Consequently, the plating film that is transformed to soft magnetic by such a method can be hardly utilized for a soft magnetic backing layer of a perpendicular magnetic recording medium.

While studies to reduce the surface roughness were made by polishing a Ni-P plating film after heat-treatment, a smooth surface

was hardly obtained by polishing the film that was crystallized by the heat-treatment. This is because the crystal of metallic nickel and the crystal of intermetallic compound Ni_3P have different hardness and exhibit very different workability.

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As described above, conventional technologies have been difficult to provide a backing layer of a perpendicular magnetic recording layer that allows high density recording with a low production cost and mass productivity.

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In addition, a soft magnetic plating film of a substrate for a perpendicular magnetic recording medium has to be designed to have the values of a surface roughness and a surface hardness that are appropriate to use for a substrate.

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Means to solve the problem

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The inventors of the present invention have made extensive studies and found that a substrate for a perpendicular magnetic recording medium with mass productivity, functioning as a soft magnetic backing layer of a perpendicular magnetic recording medium, and ensuring surface hardness, can be obtained when a soft magnetic underlayer having a thickness of more than or equal to 3 μm composed of a Ni-P alloy containing phosphorus in the range of 0.5 wt% to 6 wt% is formed on a nonmagnetic base of an aluminum

alloy by means of an electroless plating method.

The inventors also have found that the same effects as described above can also be obtained, after forming a nonmagnetic underlayer of a Ni-P alloy on a nonmagnetic base of an aluminum alloy by electroless plating, by further forming a soft magnetic underlayer of a Ni-P alloy containing phosphorus in a range of 0.5 wt% to 6 wt% on the nonmagnetic underlayer. Here, the thickness of the nonmagnetic underlayer is in the range of 0.5 μm to 7 μm , the thickness of the soft magnetic underlayer is thicker than or equal to 0.3 μm , and the sum of the thicknesses of the nonmagnetic underlayer and the soft magnetic underlayer is thicker than or equal to 3 μm .

By the intervention of the nonmagnetic underlayer between the aluminum alloy base and the soft magnetic underlayer, adhesion between the nonmagnetic base of an aluminum alloy and the soft magnetic underlayer of a Ni-P alloy can be made firmer. For this purpose, the thickness of the nonmagnetic underlayer is necessarily more than or equal to 0.5 μm .

Thickness of the soft magnetic underlayer is necessarily more than or equal to 0.3 μm to function as a soft magnetic backing layer of a perpendicular magnetic recording medium allowing high density recording.

Each thickness of the soft magnetic underlayer and the nonmagnetic underlayer is preferably less than or equal to 7 μm from the viewpoint of manufacturing cost. To guarantee hardness of the substrate surface, sum of the thicknesses of the nonmagnetic underlayer and the soft magnetic underlayer is necessarily more than or equal to 3 μm .

Concerning a composition of the soft magnetic underlayer, a stable electroless plating film can hardly be formed with a phosphorus concentration less than 0.5 wt%; a phosphorus concentration more than 6 wt% cannot provide the function as a soft magnetic backing layer due to inadequately low value of saturation magnetic flux density.

Thus constructed substrate for a perpendicular magnetic recording medium is required that the surface roughness R_a of the soft magnetic underlayer is smaller than or equal to 0.5 nm and the micro waviness W_a of the surface of the soft magnetic underlayer is less than or equal to 0.5 nm. These conditions are necessary to achieve a low flying height of about 10 nm or less of a magnetic head, which performs writing and reading of information. To achieve these surface conditions, the surface of the soft magnetic underlayer is to be smoothed by polishing with free abrasive grains.

A soft magnetic Ni-P underlayer according to the present invention consists of fine crystalline grains even in an as-plated condition. Each crystalline grain has homogeneous composition, which is a solid solution of phosphorus in nickel. This composition of the soft magnetic Ni-P underlayer of the invention is substantially different from the composition of a soft magnetic Ni-P layer that is transformed from a nonmagnetic Ni-P layer by heat-treatment, the transformed Ni-P layer being composed of two types of crystals: nickel and Ni_3P . Therefore, satisfactory smoothness can be attained by nearly the same polishing process as for a conventional nonmagnetic Ni-P layer. Thus, the polishing process can take advantage of a conventional technique.

Although a substrate for a perpendicular magnetic recording medium according to the invention as described above serves the function of a soft magnetic backing layer without heat-treatment, a heat-treatment at a temperature lower than or equal to 300°C for longer than or equal to 30 minutes after forming the soft magnetic underlayer is favorable since the heat-treatment increases the saturation magnetic flux density of the soft magnetic underlayer. Because a heat-treatment within the above-indicated range of temperature and time does not cause generation of Ni_3P crystals, smoothing of the soft magnetic underlayer can be performed, as in the case without heat-treatment, by a polishing process similar to the

conventional process for a nonmagnetic Ni-P layer.

On the other hand, if a heat-treatment is conducted at a temperature higher than 300°C, a mechanism works that is similar to the process in the heat-treatment of a nonmagnetic Ni-P layer for transformation to a soft magnetic state, and such high temperature heat treatment is unfavorable because the surface roughness of a soft magnetic Ni-P layer increases and smoothing by a polishing process becomes difficult due to generation of Ni₃P crystals.

A perpendicular magnetic recording medium comprising a nonmagnetic seed layer, a magnetic recording layer, and a protective layer sequentially formed on an above-described substrate of the invention for a perpendicular magnetic recording medium is found by the inventors to exhibit excellent recording performance as a double layer perpendicular magnetic recording medium since a function of a soft magnetic backing layer is provided by the nonmagnetic underlayer on the substrate. Because the soft magnetic backing layer is formed by an electroless plating method, which is suited to mass production, the production cost is much lower than in the case the backing layer has to be formed by, for example, a sputtering method.

A soft magnetic supplement layer can be added between the soft magnetic underlayer and the nonmagnetic seed layer, the supplement

layer having a film thickness of thinner than or equal to 50 nm and a product of the thickness and the saturation magnetic flux density of larger than or equal to 150 G μm . Since both the soft magnetic supplement layer and the soft magnetic underlayer work as a soft magnetic backing layer, the performance as a double layer perpendicular magnetic recording medium enhances and besides, an effect is produced to reduce the random noises generated in the soft magnetic underlayer. The soft magnetic supplement layer has preferably a product of the film thickness and the saturated magnetic flux density of larger than or equal to 150 G μm in order to enhance performance as a soft magnetic backing layer. A film thickness thicker than 50 nm is apt to form a magnetic domain wall in the soft magnetic supplement layer and is unfavorable because of generation of spike noises and deterioration of productivity.

The surface of the soft magnetic underlayer of the substrate can be processed by texturing with free abrasive grains, and then the above-described layers are sequentially formed by sputtering. This procedure is favorable because minute defects like random scratches can be eliminated that are generated in the polishing process and unavoidably remaining on the surface of the soft magnetic underlayer.

Brief description of drawings

Fig. 1 is a schematic cross sectional view of a substrate according

to the present invention for a perpendicular magnetic recording medium, in which a soft magnetic underlayer is formed on a nonmagnetic base of an aluminum alloy.

Fig. 2 is a schematic cross sectional view of a substrate according to the present invention for a perpendicular magnetic recording medium, in which a nonmagnetic underlayer and a soft magnetic underlayer are formed on a nonmagnetic base of an aluminum alloy.

Fig. 3 shows a schematic cross sectional view of a perpendicular magnetic recording medium according to the present invention.

Fig. 4 is a schematic cross sectional view showing a structure of a perpendicular magnetic recording medium having a soft magnetic supplement layer according to the present invention.

Fig. 5 shows signal output at a recording density of 100 kFCI of perpendicular magnetic recording media having various thicknesses of the soft magnetic underlayer as functions of write current of a magnetic head.

Fig. 6 shows signal output at a recording density of 100 kFCI of perpendicular magnetic recording media having various average phosphorus concentration in the soft magnetic underlayer as functions of write current in the magnetic head.

Fig. 7 shows the magnetic flux density B_s of the peaces of the substrate for a perpendicular magnetic recording medium produced with various time interval of heat treatment, as functions of the heat treatment temperature.

Fig. 8 shows the micro waviness W_a of the surface of a perpendicular magnetic recording medium and the minimum flying height of the magnetic head over the medium as functions of the temperature of the heat treatment.

5 Fig. 9 shows the signal-to-noise ratio SNR at a recording density of 370 kFCI (flux change per inch) in relation with the thickness of the soft magnetic supplement layer.

Fig. 10 shows the micro waviness W_a of the surface of a perpendicular magnetic recording medium produced on a
10 nonmagnetic Ni-P substrate and the minimum flying height of the magnetic head over the medium as functions of the temperature of the heat treatment.

Aspect of embodiment of the invention

15 Some aspects of preferred embodiments of the present invention will be described in the following.

Fig. 1 is a schematic cross sectional view of a substrate according to the present invention for a perpendicular magnetic recording
20 medium, in which a soft magnetic underlayer 3 is formed on an aluminum alloy base 1. Fig. 2 is a schematic cross sectional view of a substrate according to the present invention for a perpendicular magnetic recording medium, in which a nonmagnetic underlayer 2 and a soft magnetic underlayer 3 are formed on an aluminum alloy

base 1.

First, the substrate shown in Fig. 1 will be described. The nonmagnetic base 1 can be made of Al-Mg alloy or the like material that is used in a substrate of a conventional hard disk. In a nonmagnetic base of aluminum alloy that is commonly used at present, high temperature heating causes deformation of the base; heating at a temperature higher than 300°C, in particular, causes the deformation significant. Consequently, the present invention is favorably applied to a nonmagnetic base composed of an aluminum alloy since the embodiment of the invention does not require heating or the embodiment of the invention can be done at a temperature lower than or equal to 300°C. A shape of the nonmagnetic base 1 is favorably a commonly used disk shape, though not limited to special forms.

The soft magnetic underlayer 3 can be formed of a Ni-P alloy on the nonmagnetic base 1 by an electroless plating method.

The soft magnetic underlayer 3 is necessarily composed of a Ni-P alloy containing phosphorus in the range of 0.5 wt% to 6 wt%. If the content of phosphorus is less than 0.5 wt%, a stable electroless plating film is hardly formed; if the phosphorus content is larger than 6 wt%, the soft magnetic underlayer 3 does not work a function of a

double layer soft magnetic underlayer of a perpendicular magnetic recording medium due to inadequately low value of the saturation magnetic flux density.

5 The thickness of the soft magnetic underlayer 3 is necessarily more than or equal to 3 μm to ensure hardness of the substrate surface. Although there is no special upper limit, the film thickness thinner than or equal to 7 μm is favorable from a viewpoint of manufacturing cost.

10 Next, the substrate for a perpendicular magnetic recording medium as shown in Fig. 2 will be described. Nonmagnetic underlayer 2 and soft magnetic underlayer 3 are sequentially laminated on a nonmagnetic base 1. The materials and the
15 compositions for the nonmagnetic substrate 1 and the soft magnetic underlayer 3 are the same as in the substrate of Fig. 1.

 The nonmagnetic underlayer 2 is formed of mainly Ni-P by an electroless plating method. A material that can be used is, for
20 example, a Ni-P alloy containing about 11 wt% of phosphorus, which is used in a substrate of a conventional hard disk.

 A thickness of each underlayer can be as follows. A thickness of the nonmagnetic underlayer 2 is preferably thicker or equal to 0.5 μm

to ensure adhesion between the nonmagnetic base 1 and the soft magnetic underlayer 3. A thickness of the soft magnetic underlayer 3 thicker than or equal to 0.3 μm is necessary to function as a soft magnetic backing layer of a perpendicular magnetic recording medium. Though the upper limits of the thicknesses of the soft magnetic underlayer 3 and the nonmagnetic underlayer 2 are not regulated to the special values, the both thicknesses are preferably thinner or equal to 7 μm from the viewpoint of manufacturing cost. In addition, the sum of the thicknesses of the nonmagnetic underlayer 2 and the soft magnetic underlayer 3 is necessary to be at least 3 μm to ensure hardness of the substrate surface. The upper limit of the sum of the thicknesses is preferably 10 μm from the viewpoint of manufacturing cost though not strictly limited to this value.

The above-described nonmagnetic or soft magnetic plating film mainly composed of Ni-P can be formed by so-called Kanigen plating process using sodium hypophosphite for a reducing agent as is known in the art, while controlling the composition, temperature, and pH value of the plating bath.

In order to employ the substrate having the structure described above for a nonmagnetic substrate, a surface roughness Ra of the soft magnetic underlayer 3 is necessarily less than or equal to 0.5 nm and

a micro waviness W_a of the surface of the soft magnetic underlayer is necessarily less than or equal to 0.5 nm to attain flying height of the magnetic head, which reads and writes information, to be around 10 nm or lower. Here, the surface roughness R_a represents center line
5 surface roughness of a three dimensional image obtained by measuring the surface configuration in an area of 5 μm square using an atomic force microscope (AFM). The micro waviness W_a represents waviness in an area of 1 mm square measured through a band path band path filter for a wavelength range of 50 μm to 500 μm
10 using an optical surface configuration measuring instrument manufactured by Zygo Corporation.

To obtain such a surface configuration, the surface of the soft magnetic underlayer has to be smoothed by polishing with free
15 abrasive grains. The polishing can be performed by applying almost the same technique as for the conventional nonmagnetic Ni-P layers, as described earlier. The polishing can be conducted, for example, using a double sided polishing machine with polishing pads of urethane foam feeding abrasive of suspension of alumina or colloidal
20 silica.

A substrate for a perpendicular magnetic recording medium thus formed according to the present invention exhibits a function of a soft magnetic backing layer even in a state not subjected to heat-

treatment. However, heat-treatment, after formation of the soft magnetic underlayer, at a temperature lower than or equal to 300°C for longer than or equal to 30 minutes is effective to increase the saturation magnetic flux density of the soft magnetic underlayer. A heat-treatment at a temperature over 300°C is inadequate since it causes increase of surface roughness of the soft magnetic underlayer. For proper increase of the saturation magnetic flux density, the preferable heat-treatment temperature is in the range of 200°C to 300°C.

Fig. 3 and Fig. 4 show schematic cross sectional views of perpendicular magnetic recording media according to the present invention. The perpendicular magnetic recording medium shown in Fig 3 has a structure in which a nonmagnetic seed layer 20, a magnetic recording layer 30, and a protective layer 40 are sequentially formed on a substrate 10 of the invention. The substrate 10 is either one of the two types of substrates according to the invention illustrated in Fig. 1 and Fig. 2.

For the nonmagnetic seed layer 20, a material for favorably controlling crystal alignment and grain size of the magnetic recording layer 30 can be used without special limitation. In the case the magnetic recording layer 30 is a perpendicular magnetic film composed of a CoCr alloy, the materials that can be used for the

nonmagnetic seed layer 20 include a CoCr alloy, titanium, a titanium alloy, and ruthenium. In the case the magnetic recording layer 30 is a so-called multilayered perpendicular magnetic film in which a cobalt alloy and platinum or a cobalt alloy and palladium are
5 laminated, platinum or palladium can be used for the nonmagnetic seed layer 20. A preseed layer or an intermediate layer optionally provided on or below the nonmagnetic seed layer 20 does not interfere with the favorable effects of the present invention.

10 For the magnetic recording layer 30, any material that can carry out recording and reproduction in a perpendicular magnetic recording medium may be used. The usable material includes a CoCr alloy and so-called multilayered perpendicular magnetic film that is a lamination of cobalt alloy and platinum, or cobalt alloy and palladium,
15 for example.

The protective layer 40 can be a thin film composed mainly of carbon. A liquid lubricant layer of perfluoropolyether, for example, may be applied on the protective layer 40.

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The nonmagnetic seed layer 20, a magnetic recording layer 30, and a protective layer 40 can be formed by any thin film forming method including sputtering, CVD, vacuum deposition, and plating.

The perpendicular magnetic recording medium formed as described above exhibits favorable recording performance as a double layer perpendicular magnetic recording medium because the soft magnetic underlayer 3 on the substrate 10 functions as a soft magnetic backing layer. In addition, the soft magnetic underlayer is formed by an electroless plating method suited for mass production, there is no need to employ a sputtering method, for example, to form the soft magnetic underlayer. Consequently, the perpendicular magnetic recording medium according to the invention can be produced at a low cost.

The magnetic recording medium shown in Fig. 4 comprises a substrate 10 according to the present invention, and the layers sequentially formed on the substrate including a soft magnetic supplement layer 50, a nonmagnetic seed layer 20, a magnetic recording layer 30, and a protective layer 40. The substrate 10 is either one substrate shown in Fig. 1 or Fig. 2 according to the present invention.

The nonmagnetic seed layer 20, the magnetic recording layer 30, and the protective layer 40 can be appropriately formed of the similar materials to those in the perpendicular magnetic recording medium shown in Fig. 3. The soft magnetic supplement layer 50 has preferably a film thickness of thinner than or equal to 50 nm and a

product of the film thickness and the saturation magnetic flux density of larger than or equal to $150 \text{ G } \mu\text{m}$. For example, the supplement layer 50 can be composed of a CoZrNb amorphous soft magnetic layer from 15 to 50 nm thick exhibiting a saturation magnetic flux density of 10,000 G, or an FeTaC soft magnetic layer from 10 to 50 nm thick with a saturation magnetic flux density of 15,000 G. When a soft magnetic supplement layer 50 is provided, both the supplement layer and the soft magnetic underlayer work as a soft magnetic backing layer, resulting in enhancement of the performance as a double layer perpendicular magnetic recording medium. Besides, an effect is produced to reduce the random noise generated in the soft magnetic underlayer. The soft magnetic supplement layer preferably has a product of the film thickness and the saturation magnetic flux density of larger than or equal to $150 \text{ G } \mu\text{m}$ in order to enhance performance as a soft magnetic backing layer. A film thickness thicker than 50 nm is apt to form a magnetic domain wall in the soft magnetic supplement layer and is unfavorable because of generation of spike noises and deterioration of productivity.

The surface of the soft magnetic underlayer of the substrate can be processed by texturing with free abrasive grains, and then the above-described layers are sequentially formed by sputtering. This procedure is favorable because minute defects like random scratches can be eliminated that are generated in the polishing process and

unavoidably remaining on the surface of the soft magnetic underlayer.

Examples

Some specific examples of embodiments according to the present
5 invention will be described below.

Example 1

The nonmagnetic base was composed of an Al-Mg alloy having a diameter of 3.5 inches. After washing the surface by alkali cleaning
10 and acid etching, zincate (substituted zinc plating) was executed as an initial reaction layer for electroless Ni-P plating. Then, soft magnetic underlayers of a Ni-P alloy having various thicknesses from 0.5 μm to 10 μm were formed using the plating bath shown below. The average phosphorus concentration in the thus formed soft
15 magnetic underlayer was 4 wt%.

Plating bath (1)

	Nickel sulfate	25 g/liter
	Sodium hypophosphite	15 g/liter
20	Sodium acetate	10 g/liter
	Sodium citrate	15 g/liter
	pH	6 ± 0.1 (adjusted by NaOH and H_2SO_4)
	Bath temperature	$90 \pm 1^\circ\text{C}$

The surface of the soft magnetic underlayer was polished using

colloidal silica with average particle diameter of 30 nm and polishing pads of urethane foam to obtain a surface roughness R_a of 0.3 nm and a micro waviness W_a of 0.2 nm. Thus, a substrate for a perpendicular magnetic recording medium shown in Fig. 1 was produced. Abrasion
5 quantity removed by the polishing was about 0.2 μm in a measure converted to the film thickness.

After cleaning, the substrate was introduced into a sputtering apparatus, and heated to a substrate surface temperature of 250°C
10 for 10 seconds by a lamp heater. A titanium seed layer 10 nm thick was deposited using a titanium target. Subsequently a magnetic recording layer of a CoCrPt alloy 30 nm thick was deposited using a target of $\text{Co}_{70}\text{Cr}_{20}\text{Pt}_{10}$. Then, a carbon protective layer 8 nm thick was deposited using a carbon target, and the laminated substrate was
15 taken out from the vacuum chamber. These sputtering processes were all conducted by a DC magnetron sputtering method under an argon gas pressure of 5 mTorr. Finally, forming a liquid lubricant layer of perfluoropolyether 2 nm thick by dip-coating, a perpendicular magnetic recording medium as shown in Fig. 3 was produced.

20 After polishing and cleaning of the substrate in this Example, heating of the substrate was carried out in the sputtering apparatus for controlling properties of the magnetic recording layer. This heat-treatment, however, being executed in a short time and at a relatively

low temperature of 250°C, scarcely caused structural change of the soft magnetic underlayer. Thus, surface roughness and waviness of the produced perpendicular magnetic recording medium were approximately equivalent to those of the substrate.

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The thus produced perpendicular magnetic recording medium was incorporated, together with a single pole type magnetic head, into a hard disk drive. After giving mechanical shock of 50 G for 1 ms to the hard disk drive, the surface of the perpendicular magnetic recording medium was observed by an optical microscope to inspect for occurrence of flaws. Table 1 shows occurrence of flaws on the medium in relation with the thickness of the soft magnetic underlayer. As Table 1 shows, the flaws were detected on the surface of a medium having a soft magnetic underlayer thinner than 3 μm , while no flaw was detected on the surface of a medium having a soft magnetic underlayer thicker than or equal to 3 μm .

20

Table 1

thickness of soft magnetic underlayer (μm)	flaws
0.5	X
1.5	X
2.7	$\triangle$
3.1	$\bigcirc$
4.0	$\bigcirc$
7.0	$\bigcirc$
10.0	$\bigcirc$

X : flaws detected

$\triangle$: microscopic flaws detected

5 $\bigcirc$: no flaw detected

Example 2

A nonmagnetic base was composed of an Al-Mg alloy having a diameter of 3.5 inches. After washing the surface by alkali cleaning and acid etching, zincate (substituted zinc plating) was executed as an initial reaction layer for electroless Ni-P plating. Then, nonmagnetic underlayers of a Ni-P alloy having various thicknesses from 0.5 μm to 10 μm were formed using a plating bath including commercially available electroless Ni-P plating liquid for a hard disk substrate (NIMUDEN HDX manufactured by C.Uyemura & Co., Ltd.), the bath being regulated at a nickel concentration of 6.0 ± 0.1 g/L, a

pH value of 4.5 ± 0.1 , and a bath temperature of $92 \pm 1^\circ\text{C}$. The average phosphorus concentration in the nonmagnetic Ni-P plating film was 12 wt%. Subsequently, soft magnetic underlayers having various thicknesses from 0 to 10 μm were formed of Ni-P alloy with average phosphorus concentration of 4 wt% in the same manner as in Example 1. Substrates as shown in Fig. 2 for a perpendicular magnetic recording medium were produced like in Example 1. Further, perpendicular magnetic recording media as shown in Fig. 3 were produced as in Example 1.

Table 2 shows occurrence of flaws on the medium in relation with the thicknesses of the nonmagnetic underlayer and the soft magnetic underlayer evaluated by the same manner as in Example 1. The flaws were detected on the surface of a medium in which the sum of the thicknesses of the nonmagnetic underlayer and the soft magnetic underlayer was thinner than 3 μm , while the flaws on the medium surface was not detected when the sum of the thicknesses was thicker than or equal to 3 μm .

Table 2

thickness of soft magnetic underlayer (μm)	thickness of nonmagnetic underlayer (μm)	sum of the thicknesses	flaws
0.0	5.0	5.0	○
0.5	1.0	1.5	X
0.5	3.0	3.5	○
1.5	0.5	2.0	X
1.5	1.2	2.7	△
1.5	1.8	3.3	○
2.7	1.0	3.7	○
3.1	0.5	3.6	○

X : flaws detected

△ : microscopic flaws detected

5 ○ : no flaw detected

Recording performance was measured on these perpendicular magnetic recording media using a single pole type magnetic head for a perpendicular magnetic recording medium employing spinning stand tester. Fig. 5 shows signal output at a recording density of 100 kFCI (flux change per inch) as functions of write current of a magnetic head. When the thickness of the soft magnetic underlayer was zero, that is, without a soft magnetic underlayer, practically no signal output was obtained. When the thickness of the soft magnetic underlayer was thinner than 0.3 μm , signal output was relatively low and the signal output did not saturate with increase of the write

current. When the saturation of the signal output is slow with increase in the write current as in these cases, large current is necessary for generating large output. Further in the region of unsaturated signal output, the signal output greatly changes with variation of the write current, which is unfavorable for practical application. On the other hand, when the thickness of the soft magnetic underlayer was thicker than or equal to 0.3 μm , sufficient signal output was gained. Moreover, the signal output saturated at low current value. Thus, such media are practically useful. When the media having the same thickness of the soft magnetic underlayer exhibited the equivalent dependence of the signal output on the write current, despite different thickness of the nonmagnetic underlayers.

Example 3

Substrates as shown in Fig. 2 for a perpendicular magnetic recording medium were produced in the same manner as in Example 2 except that the nonmagnetic underlayer was 1.0 μm thick, the soft magnetic underlayer was 2.7 μm thick, and the average phosphorus concentration in the soft magnetic underlayer was varied in a range of 0.3 wt% to 9 wt% by varying the conditions of the plating bath in such a range as shown below. Perpendicular magnetic recording media were also produced in the same manner as in Example 1.

Plating bath (2)

Nickel sulfate 10 -35 g/liter

Sodium hypophosphite 10 -30 g/liter

Sodium acetate 10 g/liter

5 Sodium citrate 15 g/liter

pH 5.0 - 6.5 (adjusted by NaOH and H₂SO₄)

Bath temperature 75 - 95°C

When the phosphorus concentration was 0.3 wt%, the plating bath
 10 was found very unstable and unsuited for mass production.

Measurements of the recording performance were made on the
 produced media in the same manner as in Example 2. Fig. 6 shows
 signal output at a recording density of 100 kFCI as functions of write
 15 current in the magnetic head. When the average phosphorus
 concentration in the soft magnetic underlayer is less than or equal to
 6 wt%, sufficient signal output was obtained. At 7 wt%, the signal
 output decreased and saturation of the output became slow, thus, the
 function is inadequate for a soft magnetic backing layer.

20

Example 4

Substrates as shown in Fig. 2 for a perpendicular magnetic
 recording medium were produced in the same manner as in Example
 2 except that the average phosphorus concentration in the soft

magnetic underlayer was 4 wt%, the nonmagnetic underlayer was 1.0 μm thick, the soft magnetic underlayer was 2.7 μm thick, and heat treatment was conducted after formation of the soft magnetic underlayer at a temperature in a range of 100°C to 350°C and for a
5 time interval in a range of 20 minutes to 60 minutes.

A piece of sample of 8 mm square was cut from each of the thus produced substrates at the radial position of about 30 mm. The saturation magnetic flux density of each sample was measured using
10 a vibrating sample magnetometer VSM with the maximum applying field of 10 kOe. Fig. 7 shows the saturation magnetic flux density B_s of the pieces of samples of the substrate for a perpendicular magnetic recording medium produced with various time interval of heat treatment, as functions of the heat treatment temperature. As is
15 apparent from the figure, the heat treatment increases the saturation magnetic flux density of the soft magnetic underlayer from the saturation magnetic flux density of about 0.15 T of the unheated samples. The saturation magnetic flux density was increased to about 0.3 T by heat treatment at a temperature from 200°C to 300°C
20 for 30 minutes or longer. It has been also shown that heating for more than 30 minutes does not further increase the saturation magnetic flux density in this temperature range, and the heating time of 30 minutes has been found sufficient for the B_s enhancement. In the case of the heat treatment of 350°C, the nonmagnetic

underlayer was magnetized; consequently, the accurate B_s measurement of the soft magnetic underlayer was impossible.

Example 5

5 Substrates as shown in Fig. 2 for a perpendicular magnetic recording medium were produced in the same manner as in Example 2 except that the average phosphorus concentration in the soft magnetic underlayer was 4 wt%, the nonmagnetic underlayer was 1.0 μm thick, the soft magnetic underlayer was 2.7 μm thick, and heat
10 treatment was conducted after formation of the soft magnetic underlayer at a temperature in a range of 100°C and 350°C for 60 minutes. Perpendicular magnetic recording media as shown in Fig 3 were further produced in the same manner as in Example 1.

15 The micro waviness W_a of the surface of each medium was measured in an area of 1 mm square through a band path filter for a wavelength range of 50 μm to 500 μm using an optical surface configuration measuring instrument manufactured by Zygo Corporation. In addition, the minimum flying height of the magnetic
20 head over the medium was measured in the following way. A medium is rotated in a spinning stand, and a magnetic head carrying a piezoelectric element flies over the medium. A relationship between the rotating speed of the medium and the head flying height has been obtained previously. The rotating speed is gradually decreased until

the voltage of the piezoelectric element abruptly increases at a certain rotating speed. This rotating speed is converted to the head flying height to obtain the minimum head flying height. Fig. 8 shows the micro waviness W_a and the minimum flying height of the magnetic head as functions of the temperature of heating the soft magnetic underlayer. The micro waviness W_a is nearly constantly about 0.2 nm up to about 200°C; the heating to 300°C a little increased the W_a value to about 0.4 nm; the heating at 350°C sharply increases the micro waviness W_a to 0.8 nm. The head flying height is kept at a low value of about 10 nm at a heating temperature up to 300°C. At 350°C, the flying height suddenly deteriorates. Thus, the heat treatment temperature has been found necessarily lower than or equal to 300°C in order to retain the low flying height of the head without increase of the micro waviness W_a .

Example 6

A substrate for a perpendicular magnetic recording medium as shown in Fig. 2 was produced in the same manner as in Example 2 except that the nonmagnetic underlayer was 1.0 μm thick, the soft magnetic underlayer was 2.7 μm thick, and a heat treatment at 250°C for 60 minutes was conducted after formation of the soft magnetic underlayer. After cleaning, the substrate was introduced into a sputtering apparatus, in which a soft magnetic supplement layer of a NiFe alloy having a film thickness in a range of 0 to 100 nm was

formed using a target of $\text{Ni}_{80}\text{Fe}_{20}$. Subsequently, substrate heating and the followed processes were executed in the same manner as in Example 1, to produce a perpendicular magnetic recording medium as shown in Fig. 4. The thus formed soft magnetic supplement layer
5 exhibited saturation magnetic flux density of 10,000 G.

Recording performance was measured on these perpendicular magnetic recording media employing a single pole type magnetic head for a perpendicular magnetic recording medium using a
10 spinning stand tester. Fig. 9 shows signal-to-noise ratio SNR at a recording density of 370 kFCI (flux change per inch) as functions of thickness of the soft magnetic supplement layer.

The SNR values are inferior when the thickness of the soft
15 magnetic supplement layer is thinner than 15 nm, that is, the product of the thickness and the saturation magnetic flux density is less than 150 G μm . By forming a soft magnetic supplement layer having a thickness larger than or equal to 15 nm, the SNR has improved by 0.5 dB to 1 dB as compared with the case without a soft
20 magnetic supplement layer. The SNR is nearly constant in the region of thickness larger than or equal to 15 nm. Media having a soft magnetic supplement layer with a thickness larger than or equal to 50 nm, however, generated spike noises that can be assumed originated in the soft magnetic supplement layer. Consequently, such

media were improper for perpendicular magnetic recording media.

Comparative Example

A conventional hard disk substrate comprising an aluminum
5 alloy base and a nonmagnetic Ni-P underlayer on the base was used
for a substrate for a magnetic recording medium of the Comparative
Example. The substrate was heated at a temperature in the range of
100°C and 350°C for 60 minutes and then cleaned. As in the Example
1, the substrate was heated at 250°C for 10 seconds by a lamp heater
10 and then deposition processes were conducted for a titanium seed
layer 10 nm thick, a CoCrPt alloy magnetic recording layer 30 nm
thick, and a carbon protective layer 8 nm thick. The deposited
substrate was taken out from the vacuum chamber. A liquid
lubricant layer 2 nm thick was formed of perfluoropolyether by a dip-
15 coating method, to obtain a perpendicular magnetic recording
medium. Measurements of the micro waviness W_a of the medium
surface and the minimum flying height of the magnetic head were
made on the produced media in the same manner as in Example 5.
Fig. 10 shows the micro waviness W_a and the minimum flying height
20 of the magnetic head as functions of the temperature of heating the
hard disk substrate. Heating temperatures lower than or equal to
250°C resulted in the micro waviness W_a and the flying height of the
small values of about 0.2 nm and lower than or equal to 10 nm,
respectively. At the heating temperature of 300°C, the micro

waviness W_a and the flying height increased a little. At 350°C, the micro waviness W_a abruptly increased to larger than 1 nm, and the flying height rose to about 30 nm. When the heating temperature was lower than or equal to 300°C, the nonmagnetic Ni-P film was not
5 adequately transformed to a soft magnetic state.

As described above, according to the present invention, a substrate for a perpendicular magnetic recording medium with mass productivity, functioning as a soft magnetic backing layer of a
10 perpendicular magnetic recording medium, and ensuring surface hardness, can be obtained when a soft magnetic underlayer having a thickness of more than or equal to 3 μm composed of a Ni-P alloy containing phosphorus in the range of 0.5 wt% to 6 wt% is formed on a nonmagnetic base of an aluminum alloy by means of an electroless
15 plating method.

The same effects as described above can also be obtained, after forming a nonmagnetic underlayer mainly composed of a Ni-P alloy on a nonmagnetic base of an aluminum alloy by electroless plating, by
20 further forming a soft magnetic underlayer of a Ni-P alloy containing phosphorus in a range of 0.5 wt% to 6 wt% on the nonmagnetic underlayer. Here, the thickness of the nonmagnetic underlayer is in the range of 0.5 μm to 7 μm , the thickness of the soft magnetic underlayer is thicker than or equal to 0.3 μm , and the sum of the

thicknesses of the nonmagnetic underlayer and the soft magnetic underlayer is thicker than or equal to 3 μm .

By the intervention of the nonmagnetic underlayer between the
5 nonmagnetic base of an aluminum alloy and the soft magnetic underlayer, adhesion between the nonmagnetic base of an aluminum alloy and the soft magnetic underlayer of a Ni-P alloy film can be made firmer. For this purpose, the thickness of the nonmagnetic underlayer is necessarily more than or equal to 0.5 μm .
10 Thickness of the soft magnetic underlayer is necessarily more than or equal to 0.3 μm to function as a soft magnetic backing layer of a perpendicular magnetic recording medium that allows high density recording. To guarantee hardness of the substrate surface, sum of the thicknesses of the nonmagnetic underlayer and the soft magnetic
15 underlayer is necessarily more than or equal to 3 μm .

Concerning a composition of the soft magnetic underlayer, a stable electroless plating film can hardly be formed with a phosphorus concentration less than 0.5 wt%; a phosphorus
20 concentration more than 6 wt% cannot provide the function as a soft magnetic backing layer due to too low value of saturation magnetic flux density.

Thus-constructed substrate for a perpendicular magnetic

recording medium is required that the surface roughness Ra of the soft magnetic underlayer is smaller than or equal to 0.5 nm and the micro waviness Wa of the surface of the soft magnetic underlayer is less than or equal to 0.5 nm, which conditions are necessary to

5 achieve a low flying height of about 10 nm or less of a magnetic head, which performs recording of information. To achieve these surface conditions, the surface of the soft magnetic underlayer is to be smoothed by polishing with free abrasive grains.

10 The soft magnetic Ni-P underlayer of the invention can exhibit satisfactory smoothness by executing nearly the same polishing process as for a conventional nonmagnetic Ni-P layer. Thus, the polishing process can take advantage of a conventional technique.

15 Although a substrate for a perpendicular magnetic recording medium according to the invention as described above serves the function of a soft magnetic backing layer without heat-treatment, a heat-treatment at a temperature of lower than or equal to 300°C for longer than or equal to 30 minutes after forming the soft magnetic
20 underlayer is favorable since the heat-treatment increases the saturation magnetic flux density of the soft magnetic underlayer. Smoothing of the soft magnetic underlayer in this case can also be performed by a polishing process similar to the conventional process of a nonmagnetic Ni-P layer.

On the other hand, if a heat-treatment is conducted at a temperature higher than 300°C, a mechanism works that is similar to the process in the heat-treatment of a nonmagnetic Ni-P layer for transformation to a soft magnetic state, and such high temperature heat treatment is unfavorable because the surface roughness of a soft magnetic Ni-P layer increases and smoothing by a polishing process becomes difficult due to generation of Ni₃P crystals.

A perpendicular magnetic recording medium comprising a nonmagnetic seed layer, a magnetic recording layer, and a protective layer sequentially formed on an above-described substrate of the invention has been found by the inventors to exhibit excellent recording performance as a double layer perpendicular magnetic recording medium since a function of a soft magnetic backing layer is provided by the soft magnetic underlayer on the substrate. Because the soft magnetic underlayer is formed by an electroless plating method, which is suited to mass production, the production cost is much lower than in the case the soft magnetic underlayer has to be formed by, for example, a sputtering method.

A soft magnetic supplement layer can be added between the soft magnetic underlayer and the nonmagnetic seed layer, the supplement layer having a film thickness of thinner than or equal to 50 nm and a product of the thickness and the saturation magnetic flux density of

larger than or equal to $150 \text{ G } \mu\text{m}$. Since both the soft magnetic supplement layer and the soft magnetic underlayer work as a soft magnetic backing layer, the performance as a double layer perpendicular magnetic recording medium enhances and besides, an effect is produced to reduce the random noises generated in the soft magnetic underlayer. The soft magnetic supplement layer has preferably a product of the film thickness and the saturated magnetic flux density of larger than or equal to $150 \text{ G } \mu\text{m}$ in order to enhance performance as a soft magnetic backing layer. A film thickness thicker than 50 nm is apt to form a magnetic domain wall in the soft magnetic supplement layer and is unfavorable because of generation of spike noises and deterioration of productivity.

The surface of the soft magnetic underlayer of the substrate can be processed by texturing with free abrasive grains, and then the above-described layers are sequentially formed by sputtering. This procedure is favorable because minute defects like random scratches can be eliminated that are generated in the polishing process and unavoidably remaining on the surface of the soft magnetic underlayer.

Advantageous Effect of the invention

As described so far, according to the present invention, a substrate for a perpendicular magnetic recording medium can be obtained that allows mass production, the function as a soft magnetic

backing layer of a perpendicular magnetic recording medium, and the ensured surface hardness. By using such a substrate, a perpendicular magnetic recording medium with satisfactory performances can be achieved.

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1. A substrate for a perpendicular magnetic recording medium comprising:

a nonmagnetic base composed of an aluminum alloy; and

5 a soft magnetic underlayer formed on the base by an electroless plating method, the soft magnetic underlayer being composed of a Ni-P alloy containing phosphorus in a range of 0.5 wt% to 6 wt%, having a thickness of thicker than or equal to 3 μm , and being utilized as at least a portion of the soft magnetic backing layer.

10 2. A substrate for a perpendicular magnetic recording medium comprising:

a nonmagnetic base composed of an aluminum alloy;

a nonmagnetic underlayer principally composed of a Ni-P alloy

15 formed on the base by an electroless plating method; and

a soft magnetic underlayer composed of a Ni-P alloy containing phosphorus in a range of 0.5 wt% to 6 wt% formed on the nonmagnetic underlayer by an electroless plating method, wherein

20 the nonmagnetic underlayer has a thickness in a range of 0.5 μm to 7 μm ; the soft magnetic underlayer has a thickness larger than or equal to 0.3 μm ; a sum of the thickness of the nonmagnetic underlayer and the thickness of the soft magnetic underlayer is larger than or equal to 3 μm ; and being utilized as at least a portion of the soft magnetic backing layer.

3. The substrate according to claim 1 or claim 2, wherein a surface of the soft magnetic underlayer has a surface roughness Ra of less than or equal to 0.5 nm and a micro waviness Wa of less than or equal to 0.5 nm.

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4. A method for manufacturing the substrate that is defined by any one of claims 1 through 3, the method comprising at least a step of heat-treating the substrate at a temperature lower than or equal to 300°C for 30 minutes or longer after a step of forming the soft

10 magnetic underlayer.

5. A method for manufacturing the substrate that is defined by any one of claims 1 through 3, the method comprising at least a step of smoothing a surface of the soft magnetic underlayer by polishing

15 using free abrasive grains.

6. A perpendicular magnetic recording medium comprising at least a nonmagnetic seed layer, a magnetic recording layer, and a protective layer sequentially formed on the substrate that is defined

20 by any one of claims 1 through 3, wherein the perpendicular magnetic recording medium utilizes the soft magnetic underlayer as at least a portion of a soft magnetic backing layer.

7. The perpendicular magnetic recording medium according to

claim 6 further comprising a soft magnetic supplement layer between the soft magnetic underlayer and the nonmagnetic seed layer, the soft magnetic supplement layer having a film thickness of thinner than or equal to 50 nm and a product of the film thickness and a saturation magnetic flux density of larger than or equal to 150 G μm .

8. A method for manufacturing the perpendicular magnetic recording medium that is defined by claim 6, the method comprising a step of texturing a surface of the soft magnetic underlayer using free abrasive grains, and steps of sequentially forming layers including the nonmagnetic seed layer, the magnetic recording layer, and the protective layer by a sputtering method.

9. A method for manufacturing the perpendicular magnetic recording medium that is defined by claim 7, the method comprising a step of texturing a surface of the soft magnetic underlayer using free abrasive grains, and steps of sequentially forming layers including the nonmagnetic seed layer, the magnetic recording layer, and the protective layer by a sputtering method.