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Magnetic Recording Medium

Technical field of the invention

The present invention relates in general to a magnetic recording medium and in particular to a magnetic recording medium used in a hard disc drive (HDD) and the like mounted on equipment such as personal computers (PCs), network terminal devices, or audio visual (AV) apparatuses.

Background of the invention

A conventional magnetic recording medium used in an HDD of a PC comprises an underlayer 2, an intermediate layer 3, a magnetic layer 4, and a protective layer 5 sequentially formed on a substrate 1 of aluminum or glass, as illustrated in Fig. 7. Information is recorded in the magnetic layer 4 as a magnetized recording bit on the magnetic recording medium. Of such recording media, a medium in which a direction of magnetization of the recording bit is horizontal direction (or in-plane direction) in relation to the substrate surface is called a horizontal (or longitudinal or in-plane) recording medium. A medium in which the magnetization direction of the recording bit is vertical is called a vertical (or perpendicular) recording medium. All media put to practical use to date are of horizontal recording system. However, the media of vertical recording system are actively being studied in recent years.

A magnetic layer 4 of a magnetic recording medium is generally composed of a polycrystalline thin film of cobalt system in which fine crystallites of cobalt are formed into a film shape. A crystal structure of each cobalt crystallite is the hexagonal closest packed (hcp)

5 structure of a hexagonal crystal system. To record information by magnetizing the magnetic layer 4 with this structure in the horizontal (in-plane) direction in relation to the surface of the substrate 1, the polycrystalline magnetic film of cobalt system must be formed so that the axis of easy magnetization, c-axis out of the a-
10 axis and the c-axis shown in Fig. 8, orients with preference in the horizontal (in-plane) direction in relation to the substrate 1. In a perpendicular recording medium, the cobalt c-axis must be predominantly oriented in the direction vertical to the substrate 1.

15 Each crystal grain is desired minimized to achieve high recording density. In addition, the crystal grain is desired to be isolated and separated each other so that magnetic interaction between the crystal grains is decreased. Consequently, polycrystalline thin film of a CoCr system has been used for the magnetic layer 4. This cobalt alloy
20 containing 10 to 20 % of chromium separates into a cobalt-rich ferromagnetic phase and a chromium-rich nonmagnetic phase by phase separation. The chromium-rich nonmagnetic phase tends to precipitate at the grain boundary. Thus, the cobalt-rich ferromagnetic crystal grains are made minute, and isolated and

separated each other.

In order to achieve minimization and separation of crystal grains and, at the same time, to accomplish the predominant c-axis alignment in the horizontal (in-plane) direction, conventionally employed practical technologies have formed an underlayer of a polycrystalline thin film made of chromium or chromium alloy on a substrate of aluminum or glass and a magnetic layer of CoCr system on this underlayer.

There are two reasons why chromium or chromium alloy has been used for the underlayer. First of the two is as described below. The magnetic layer 4 is a material of a CoCr system and the chromium-rich nonmagnetic phase precipitates surrounding the cobalt-rich ferromagnetic crystalline grains. Consequently, chromium of the underlayer 2 aids to minimize and separate the crystalline grains in the magnetic layer by promoting precipitation of the chromium-rich nonmagnetic phase in the magnetic layer 4. Second reason is because the chromium in the underlayer has an effect to predominantly align a c-axis of the cobalt crystal of the magnetic layer 4 in a horizontal (or in-plane) direction. This effect arises from good lattice matching of the chromium with the CoCr alloy crystal although the crystal structure of chromium is a body centered cubic (bcc) structure belonging to a cubic crystal system.

Such a magnetic recording medium is produced by sequentially forming a chromium underlayer, a CoCr alloy magnetic layer, and a carbon protective layer on a disk shape aluminum substrate with a NiP plating by means of a sputtering method. A magnetic recording
5 medium using a glass substrate is similarly produced by sequentially forming a NiAl seed layer, a chromium underlayer, a CoCr magnetic layer, and a protective layer on a glass substrate by means of a sputtering method.

10 Problem to be solved by the invention

However, in a conventional magnetic recording medium using a CoCr magnetic layer, a chromium underlayer, and a substrate of aluminum or glass, the substrate needs to be heated up to a temperature between about 200°C and 300°C when the magnetic layer
15 is formed by a sputtering method. Without the substrate heating, a high coercive force H_c required for achieving high recording density cannot be attained.

A method for forming a magnetic layer with high coercive force is
20 known, in which relatively high concentration of platinum in the range from 5 to 10 % with respect to cobalt atoms is contained in the CoCr magnetic layer. Even if a magnetic layer containing relatively high concentration of platinum is used, however, high coercive force cannot be attained without substrate heating when a chromium

underlayer is used. The reason may be supposed as follows. If substrate heating is not executed, phase separation of the CoCr alloy into a cobalt-rich phase and a chromium-rich phase does not enough progress, resulting in insufficient isolation of cobalt crystalline grains.

- 5 Predominant in-plane alignment of the c-axis of the cobalt crystals is also insufficient.

Because a plastic substrate cannot allow substrate heating in a deposition process, a magnetic recording medium that copes with
10 high recording density cannot be manufactured. A magnetic recording medium using an aluminum substrate or a glass substrate also involves a problem that the inevitable substrate heating in sputtering steps needs additional cost.

15 The present invention has been made in view of these problems and an object of the invention is to provide a magnetic recording medium with excellent magnetic property without substrate heating in sputtering steps.

20 Means to solve the problem

The inventors of the present invention have made extensive studies and found that a magnetic recording medium using a plastic substrate can be produced without substrate heating in sputtering steps and exhibits an excellent magnetic property when the magnetic

recording medium has a basic structure comprising an underlayer with a bcc structure, an intermediate layer with an hcp structure and a magnetic layer with an hcp structure, and respective spacing of (110), (002), and (002) lattice planes decreases towards upper layers, 5 misfit between the spacings of lattice planes being within 10 %.

Specifically, a magnetic recording medium according to the present invention comprises a substrate, an underlayer with a body centered cubic crystal structure formed on the substrate, an 10 intermediated layer with a hexagonal closest packed crystal structure formed on the underlayer, a magnetic layer composed principally of cobalt with the hexagonal closest packed structure formed on the intermediate layer, and a protective layer formed on the magnetic layer; and a relation $d_1 > d_2 > d_3$ holds, where d_1 is a spacing between 15 (110) planes of the underlayer; d_2 is a spacing between (002) planes of the intermediate layer; and d_3 is a spacing between (002) planes in the magnetic layer.

Advantageously, a relation $0.0 < (d_1 - d_2) / d_1 < 0.1$ holds.

20 Advantageously, a relation $0.0 < (d_2 - d_3) / d_2 < 0.1$ holds.

Advantageously, relations

$0.0 < (d_1 - d_2) / d_1 < 0.1$ and $0.0 < (d_2 - d_3) / d_2 < 0.1$

simultaneously hold.

Advantageously, a material of the magnetic layer contains a nonmetallic element or a nonmetallic compound in a proportion from 5 to 20 mol % with respect to content of the cobalt.

5 Advantageously, a material of the magnetic layer contains platinum in a proportion of 10 to 50 at % with respect to content of the cobalt.

10 Advantageously, a material of the magnetic layer contains a nonmetallic element or a nonmetallic compound in a proportion of 5 to 20 mol % with respect to a content of the cobalt and platinum in a proportion of 10 to 50 at % with respect to the content of the cobalt.

15 Advantageously, the intermediate layer is principally composed of Ru, Re, Os, or Tc.

20 Advantageously, the intermediate layer is principally composed of an intermetallic compound selected from Rh_3W , Ni_3Sn , Ni_3Zr , and Co_3W .

Advantageously, the underlayer is principally composed of Ta, Nb, W, or Mo.

Advantageously, a magnetic recording medium of the invention

further comprises a seed layer composed of an intermetallic compound with a composition of CoTi, CoZr, CuZr, FeTi, or NiTi

Advantageously, a direction of magnetization for recording
5 information in the magnetic layer is horizontal in relation to the substrate.

Advantageously, at least one of the underlayer, the intermediate layer, the magnetic layer, and the protective layer is formed by means
10 of a sputtering method.

Advantageously, a thickness of the underlayer is in the range from 5 to 20 nm.

15 Advantageously, a thickness of the intermediate layer is in the range from 5 to 50 nm.

Advantageously, a thickness of the magnetic layer is in the range from 5 to 20 nm.

20

Advantageously, the intermediate layer consists of a first intermediate layer with a hexagonal crystal structure formed on the underlayer and a second intermediate layer with a hexagonal crystal structure formed between the first intermediate layer and the

magnetic layer, and a relation

$$d_1 > d_4 > d_5 > d_3$$

holds, where d_4 is a spacing between (002) planes of the first intermediate layer and d_5 is a spacing between (002) planes of the
5 second intermediate layer.

Advantageously, the underlayer consists of a first underlayer with a body centered cubic crystal structure formed on the substrate and a second underlayer with a body centered cubic crystal structure
10 formed between the first underlayer and the intermediate layer, and a relation

$$d_6 > d_7 > d_2$$

holds, where d_6 is a spacing between (110) planes in the first underlayer and d_7 is a spacing between (110) planes in the second
15 underlayer.

Advantageously, a relation

$$0.02 \leq (d_1 - d_2) / d_1$$

further holds.

20

Advantageously, a relation

$$0.02 \leq (d_2 - d_3) / d_2$$

further holds.

Advantageously, relations

$$0.02 \leq (d_1 - d_2) / d_1 \text{ and } 0.02 \leq (d_2 - d_3) / d_2$$

simultaneously hold.

5 Brief description of drawings

Figure 1 is a schematic cross sectional view of a magnetic recording medium of first aspect of embodiment according to the present invention.

10 Figure 2 is a chart showing definitions of spacings of lattice planes perpendicular to the substrate in the layers of a magnetic recording medium of first aspect of embodiment according to the present invention.

15 Figure 3 is an illustration showing schematically a bcc crystal structure.

Figure 4 is a chart showing definitions of lattice constants in the layers of a magnetic recording medium of first aspect of embodiment according to the present invention.

20 Figure 5 is a chart showing relations between the spacings of lattice planes and the lattice constants in the layers of a magnetic recording medium of first aspect of embodiment according to the present invention.

Figure 6 is a schematic cross sectional view of a magnetic recording medium of second aspect of embodiment according to the

present invention.

Figure 7 is a schematic cross sectional view showing a construction of a conventional magnetic recording medium.

Figure 8 is an illustration showing schematically an hcp crystal
5 structure.

Aspects of embodiments of the present invention

Now, aspects of embodiments of the present invention will be described in detail in the following with reference to accompanying
10 drawings.

First aspect of embodiment

Fig. 1 is a cross sectional view showing a construction of a magnetic recording medium of first aspect of embodiment of the
15 invention. A magnetic recording medium of the first aspect comprises an underlayer 102 of a nonmagnetic film with a body centered cubic (bcc) crystal structure formed on a substrate 101. On the underlayer 102 formed is an intermediate layer 103 of a nonmagnetic film with a hexagonal closest packed (hcp) crystal structure. On the
20 intermediate layer 103 formed is a magnetic layer 104 for recording information of a magnetic film principally composed of cobalt and having a hexagonal closest packed crystal structure, wherein a direction of magnetization is horizontal in relation to the substrate 101. Here, 'principally composed of cobalt' means 'containing cobalt

in a proportion of more than about 50 at %'. On the magnetic layer 104 formed is a protective layer 105 for protecting the magnetic layer and a magnetic head.

5 Fig. 2 shows definitions of spacings d_1 , d_2 , and d_3 of lattice planes vertical to the substrate in the layers of a magnetic recording medium of this aspect of embodiment. d_1 is defined as a spacing between (110) planes in the underlayer 102; d_2 is defined as a spacing between (002) planes in the intermediate layer 103; and d_3 is defined
10 as a spacing between (002) planes in the magnetic layer 104. The materials used for the underlayer 102, the intermediate layer 103, and the magnetic layer 104 hold the following relation between the spacings between crystal lattice planes thereof:

$$d_1 > d_2 > d_3 . \quad (1)$$

15

Misfit Δ_1 of spacings of lattice planes between the underlayer and the intermediate and misfit Δ_2 of spacings of lattice planes between the intermediate layer and the magnetic layer are defined by

$$\Delta_1 = (d_1 - d_2) / d_1 \text{ and}$$

20 $\Delta_2 = (d_2 - d_3) / d_2.$

Then, the following relations simultaneously hold.

$$0.0 < \Delta_1 < 0.1 \quad \text{and} \quad 0.0 < \Delta_2 < 0.1 \quad (2)$$

Each of the spacings of lattice planes d_1 , d_2 , and d_3 of the

underlayer 102, the intermediate layer 103, and the magnetic layer 104, respectively, has the following relation with the lattice constant of each crystal lattice.

- 5 There exists only one lattice constant 'a' in a bcc structure as shown in Fig. 3. Provided a_1 be a lattice constant in the underlayer 102 as shown in Fig. 4, the spacing d_1 between (110) planes is

$$d_1 = a_1 / \sqrt{2}.$$

- 10 There exist two lattice constants 'a' and 'c' as shown in Fig. 8 in the intermediate layer 103 and in the magnetic layer 104, both of which have hcp structure. Let a_2 and c_2 be lattice constants in the intermediate layer 103, and a_3 and c_3 be lattice constants in the magnetic layer 104, as shown in Fig. 4. Then, the spacing d_2 of
15 lattice planes in the intermediate layer 103 and the spacing d_3 of lattice planes in the magnetic layer 104 are given by

$$d_2 = c_2 / 2, \quad \text{and} \quad d_3 = c_3 / 2,$$

respectively. Fig. 5 summarizes the relations between the spacings of lattice planes and the lattice constants.

20

Using these relations, the equations (1) and (2) can be transformed to the following equations:

$$a_1 / \sqrt{2} > c_2 / 2 > c_3 / 2 \quad (3)$$

$$0.0 < \Delta 1 = (a_1 / \sqrt{2} - c_2 / 2) / a_1 / \sqrt{2} < 0.1 \quad \text{and}$$

$$0.0 < \Delta 2 = (c_2 - c_3) / c_2 < 0.1 \quad (4)$$

An actual method for manufacturing a magnetic recording
 5 medium of this aspect of embodiment will be described below. When
 an underlayer 102 with a body centered cubic structure is formed on
 a substrate 101 by a sputtering method, for example, each crystal
 grain generally grows in the direction where the crystal planes of
 (100), (110), (111), or (211) is parallel to the substrate surface. In a
 10 crystalline grain with a body centered cubic structure, any growth
 type based on the above mentioned crystal planes has a (110) crystal
 plane in the direction vertical to the substrate surface. On the
 underlayer 102, formed is an intermediate layer 103 with a hexagonal
 closest packed structure having a spacing d_2 between (002) planes
 15 vertical to the substrate surface by a sputtering method, for example,
 d_2 being smaller than the spacing d_1 .

There holds the following relation between the spacing d_1 of
 lattice planes in the underlayer 102 and the spacing d_2 of lattice
 20 planes in the intermediate layer 103.

$$d_1 = (d(110) \text{ in the underlayer})$$

$$> d_2 = (d(002) \text{ in the intermediate layer})$$

where $d(h \ k \ l)$ is a spacing of lattice planes represented by a Miller
 index $(h \ k \ l)$.

Crystals in the intermediate layer with a hexagonal closest packed structure generally include (101) planes which have a spacing of lattice planes nearly equal to the spacing d_2 of (002) planes. The (002) planes, being perpendicular to the c-axis, are important for controlling the direction of the c-axis. On the other hand, because the (101) planes are in an acute angle with the c-axis, growth of the (101) planes disturbs controlling c-axis orientation. The spacing of (101) lattice planes is smaller than the spacing d_2 of (002) planes in a crystal with a hexagonal closest packed structure:

$$d_2 = (d(002) \text{ in the intermediate layer}) \\ > (d(101) \text{ in the intermediate layer})$$

A spacing $d(h\ k\ l)$ of lattice planes in a hexagonal crystal system is represented in terms of the lattice constants a and c by:

$$1 / d(h\ k\ l)^2 = 4 (h^2 + hk + k^2) / 3 a^2 + l^2 / c^2.$$

In a hexagonal closest packed structure, c/a is about 1.63. From the above equation and the value $c/a = 1.63$, the following is deduced:

$$d(101) < c/2 = d(002).$$

Consequently, a lattice matching relation between the underlayer 102 and the intermediate layer 103 can be represented by:

$$(d(110) \text{ of the underlayer}) - (d(002) \text{ of the intermediate layer}) \\ < (d(110) \text{ of the underlayer}) - (d(101) \text{ of the intermediate layer})$$

That is,

$d_1 - d_2 < d_1 \cdot (d(101) \text{ of the intermediate layer})$.

Therefore, lattice matching with respect to the (110) planes in the crystalline grain of the underlayer 102, the (110) plane being vertical to the substrate surface, is worse for the (101) planes in the intermediate layer than for the (002) planes in the intermediate layer. As a result, in initial growth of the crystalline grains in the intermediate layer 103, the (002) planes show more tendency than the (101) planes to grow vertical to the substrate surface in continuation with the (110) plane of the underlayer 102. In other words, the crystals in the intermediate layer 103 initially grow so that the c-axis predominantly aligns parallel to the substrate surface. Further, in the relation

$(d(110) \text{ of the underlayer}) > (d(002) \text{ in the intermediate layer})$, the misfit $\Delta 1$ of spacings of lattice planes between the two layers satisfies the relation

$$0.0 < \Delta 1 = (d_1 - d_2) / d_1 < 0.1,$$

that is, the lattice misfit is less than 10 %. Accordingly, the crystals in the intermediate layer 103 can be considered to grow to a certain size with the c-axis predominantly aligning horizontal.

A magnetic layer 104 is formed on such an intermediate layer 103 that is grown with the alignment in which the c-axis is parallel to the substrate surface, as described above. The crystals of the magnetic layer 104 with a hexagonal closest packed structure have a

spacing d_3 of lattice planes in the c -axis direction smaller than the spacing d_2 of lattice planes in the intermediate layer 103 and a misfit with the intermediate layer smaller than 10 %. Then,

$$\begin{aligned} & d_2 = (d(002) \text{ in the intermediate layer}) \\ 5 \quad & > d_3 = (d(002) \text{ in the magnetic layer}). \end{aligned}$$

Since the magnetic layer 104 is composed of crystals of cobalt system with a hexagonal closest packed structure,

$$\begin{aligned} & d_2 = (d(002) \text{ in the magnetic layer}) \\ & > (d(101) \text{ in the magnetic layer}). \end{aligned}$$

10 Consequently, a lattice matching relation between the intermediate layer and the magnetic layer 104 can be represented by:

$$\begin{aligned} & (d(002) \text{ in the intermediate layer}) - (d(002) \text{ in the magnetic layer}) \\ & < (d(002) \text{ in the intermediate layer}) - (d(101) \text{ in the magnetic layer}). \end{aligned}$$

That is,

$$15 \quad d_2 - d_3 < d_2 - (d(101) \text{ in the magnetic layer}).$$

Therefore, lattice matching with respect to the (002) planes in the intermediate layer 103, which is vertical to the substrate surface, is superior for the (002) planes in the magnetic layer 104 than for the (101) planes in the magnetic layer 104. As a result, the magnetic
20 layer initially grows with a tendency of the (002) planes thereof vertical to the substrate surface. In other words, the crystals in the magnetic layer 104 initially grow so that the c -axis predominantly aligns parallel to the substrate surface.

Further, in the relation

($d(002)$ of the intermediate layer) > ($d(002)$ in the magnetic layer),
the misfit $\Delta 2$ of spacings of lattice planes between the two layers
satisfies the relation

5 $0.0 < \Delta 2 = (d_2 - d_3) / d_2 < 0.1,$

that is, the lattice misfit is less than 10 %. Accordingly, the crystals
in the magnetic layer 104 can be considered to grow to a certain size
with the c -axis predominantly aligning horizontal.

10 Thus, the c -axis in the intermediate layer 103 has the alignment
parallel to the substrate surface, and in the influence of such an
intermediate layer 103, the c -axis in the magnetic layer 104 has
stronger alignment parallel to the substrate surface than in the
intermediate layer 103. Because the c -axis alignment becomes
15 stronger in the upper layer as in the order of the underlayer 102, the
intermediate layer 103, and the magnetic layer 104, the c -axis of the
crystalline grains in the magnetic layer 104 in such lattice
configuration can be expected to predominantly align parallel to the
substrate surface even if substrate heating is omitted in the film
20 forming process.

Among the underlayer 102, the intermediate layer 103, and the
magnetic layer 104, the following relation exists:

spacing d_1 between (110) planes in the underlayer

> spacing d_2 between (002) planes in the intermediate layer

> spacing d_3 between (002) planes in the magnetic layer.

In addition, the misfit of spacings of lattice planes at the interface between the layers exists in a degree less than 10 %. Therefore, the grain size in the horizontal direction of the intermediate layer 103 tends to be nearly in the same size or smaller than that of the underlayer 102; and the grain size in the horizontal direction of the magnetic layer 104 tends to be nearly in the same size or smaller than that of the intermediate layer 103. As a result, minimization of the crystalline grains in the magnetic layer 104 can be achieved.

Because the spacing of lattice planes in an upper layer is smaller than that of the corresponding spacing of a lower layer, the intermediate layer 103 is likely to generate a gap at the grain boundary than the underlayer 102, and the magnetic layer 4 is likely to generate a gap at the grain boundary than the intermediate layer 103. Therefore, minimization and isolation (or separation) of crystalline grains can be achieved without substrate heating in the film forming process. In order to promote this tendency, it is preferable to increase misfit of spacings of lattice planes between the layers as long as predominant alignment of the c-axis in the horizontal direction is sufficiently attained.

Although such materials are selected in manufacturing a

conventional magnetic recording medium that the misfit between the layers is minimum, the misfit between each pair of layers in the present invention is confined in the limited range to achieve excellent magnetic performance. In particular, the relations

5 $0.02 \leq (d1 - d2) / d1$ and

$0.02 \leq (d2 - d3) / d2$

are outstanding features of the present invention.

Because minimization and isolation of the crystalline grains are
10 easily attained in the magnetic layer 104 of the invention, an element or a compound that is likely to precipitate at the grain boundary is promoted to precipitate homogeneously at the grain boundary of the cobalt crystal in the magnetic layer 104. Consequently, excellent fine structure is accomplished in the magnetic layer of a magnetic
15 recording layer.

Even using those magnetic materials, the c-axis in the intermediate layer 103 still tends to align in the horizontal direction. Accordingly, the c-axis of the cobalt crystal in the magnetic layer 104
20 aligns more strongly in the horizontal direction in relation to the substrate surface than in the intermediate layer 103.

When a material of CoPt system containing 10 to 50 at % of platinum with respect to cobalt is used for the magnetic layer aiming

at high coercive force, the spacing of lattice planes of the cobalt crystal in the magnetic layer 104 increases a little by solid solution of the platinum atoms. In that case, if a material with a hexagonal structure in which a spacing between (002) planes is larger than the
5 spacing of (002) planes of the cobalt crystal including platinum atoms of solid solution, it is expected to promote solid solution of the platinum atoms into the cobalt crystals, leading to further higher coercive force.

10 Preferably, a nonmetallic element or compound is contained in the magnetic layer in a proportion from 5 to 20 at % with respect to the content of cobalt.

Preferably, the thickness of the underlayer is in the range from 5
15 to 20 nm; the thickness of the intermediate layer is in the range from 5 to 50 nm; and the thickness of the magnetic layer is in the range from 5 to 50 nm.

The underlayer in the above-described layer construction may be
20 composed of Nb, W, or Mo as well as Ta. These metals have a bcc crystal structure and are nonmagnetic. As shown in Table 1, the spacings between (110) planes of these metals are larger than the spacing 2.142 Å between the (002) planes of the ruthenium used for the intermediate layer and the misfits are smaller than 10 %. An

alloy principally composed of these metals also may be used for the underlayer. Here, 'principally composed of' means 'containing more than about 50 at %'.

5 Table 1

	crystal structure	spacing between (110) planes (Å)	misfit with Ru (002) (%)
Ta	bcc	2.338	8.4
Nb	bcc	2.336	8.3
W	bcc	2.238	4.3
Mo	bcc	2.225	3.7

The intermediate layer may be composed of Os, Re, or Tc as well as Ru, to decrease misfit and rather improve lattice matching. These metals have an hcp crystal structure and are nonmagnetic. As shown
10 in Table 2, the spacings between (002) planes of these metals are larger than the spacing between the (002) planes of cobalt and the misfits are smaller than 10 %. When about 20 at % of platinum is added to the magnetic layer that is principally composed of cobalt, the spacing of (002) planes of the cobalt crystals increases by about 3 %.
15 An alloy principally composed of these metals also may be used for the intermediate layer. Here, 'principally composed of' means 'containing more than about 50 at %'.

Table 2

	crystal structure	spacing between (002) planes (Å)	misfit with Co (002) (%)
Os	hcp	2.160	6.3
Re	hcp	2.226	9.1
Tc	hcp	2.199	8.0
Ru	hcp	2.142	5.6
Co	hcp	2.023	0.0

The intermediate layer may be principally composed of the alloys or intermetallic compounds shown in Table 3. The crystal structure of these alloys is classified into a hexagonal crystal system and has the space group of P63/mmc, which is same as that of cobalt; thus the crystal structure of the alloys are similar to that of the cobalt. Here, 'principally composed of' means 'containing more than about 50 % in molar proportion'

Table 3

	crystal structure	spacing between (002) planes (Å)	misfit with Co (002) (%)
WRh ₃	hexagonal	2.174	6.9
Ni ₃ Sn	hexagonal	2.126	4.8
Ni ₃ Zr	hexagonal	2.121	4.6
Co ₃ W	hexagonal	2.060	1.8
Co	hcp	2.023	0.0

Second aspect of embodiment

Fig. 6 is a cross sectional view showing a construction of the second aspect of embodiment of a magnetic recording medium according to the invention. A magnetic recording medium of this aspect of embodiment comprises a seed layer 106 on the substrate 101 to improve crystal alignment. An underlayer 102 of a nonmagnetic film with a body centered cubic (bcc) structure is formed on the seed layer 106. An intermediated layer 103 of a nonmagnetic film with a hexagonal closest packed (hcp) structure is formed on the underlayer 102. A magnetic layer 104 of a magnetic film with a hexagonal closest packed structure is formed on the intermediated layer 103. A protective layer 105 is formed on the magnetic layer 104.

Crystals of the seed layer have a body centered cubic lattice, which is the same as that of the underlayer, and the space group $Pm\bar{3}m$. Thus, the crystal structure of the seed layer is similar to that of the underlayer 102 and exhibits superior lattice matching with the underlayer 102. Two component elements of the seed layer have a tendency to deposit alternately on the substrate. This tendency is similar to the case where a seed layer of NiAl is used under an underlayer of chromium in a magnetic recording medium comprising an underlayer of chromium, a magnetic layer of CoCr, and a glass substrate.

As a result, the seed layer crystals exhibit a tendency for (211)

planes thereof to align parallel to the substrate surface. Because the (211) plane of the underlayer 102 well matches to a (100) plane of the hcp lattice, alignment of the intermediate layer 103 improves and in-plane alignment of the c-axis increases. As a consequence, in-plane alignment of the c-axis of the magnetic layer 104 enhances as well.

This aspect of embodiment provides a seed layer of a thin film composed, for example, of the binary alloys or intermetallic compounds shown in Table 4 under an underlayer.

Table 4

	crystal structure	spacing between (110) planes (Å)	misfit with Ta (110) (%)
CoTi	cubic system	2.111	10.7
CoZr	cubic system	2.260	3.5
CuZr	cubic system	2.306	1.4
FeTi	cubic system	2.104	11.1
NiTi	cubic system	2.120	10.3
Ta	bcc	2.338	0.0

The lattice misfits for the case of a tantalum underlayer are given in Table 4. CoZr and CuZr exhibit small values of lattice misfit with tantalum and are suitable for producing a magnetic recording medium applying the present invention. Although CoTi, FeTi, and NiTi exhibit relatively large values of misfit with tantalum, the misfit can be made smaller when tungsten or molybdenum having a smaller

spacing between (110) planes than tantalum is used for the material of the underlayer. Accordingly, the alloys are also suitable for producing a magnetic recording medium applying the present invention.

5

Other aspects of embodiments

The intermediate layer may consist of first intermediate layer and second intermediate layer that have a crystal structure classified into a hexagonal crystal system. A magnetic recording medium in this aspect of embodiment comprises an underlayer, first intermediate layer, second intermediate layer, a magnetic layer, and a protective layer sequentially formed on a substrate. Preferably, the following relation holds among the spacing d_1 between (110) planes in the underlayer, the spacing d_4 between the (002) planes in the first intermediate layer, the spacing d_5 between the (002) planes in the second intermediate layer, and the spacing d_3 between the (002) planes in the magnetic layer:

$$d_1 > d_4 > d_5 > d_3.$$

A seed layer may be provided between the substrate and the underlayer.

The underlayer may consist of first underlayer and second underlayer that have a body centered cubic lattice structure. A magnetic recording medium in this aspect of embodiment comprises a

first underlayer, a second underlayer, an intermediate layer, a magnetic layer, and a protective layer sequentially formed on a substrate. Preferably, the following relation holds among the spacing d6 between the (110) planes in the first underlayer, the spacing d7
5 between the (110) planes in the second underlayer, the spacing d2 between the (002) planes in the intermediate layer, and the spacing d3 between the (002) planes in the magnetic layer:

$$d6 > d7 > d2.$$

A seed layer may be provided between the substrate and the
10 underlayer.

The present invention will be described more in detail with reference to some examples of preferred embodiments.

15 Examples

Example 1

An underlayer of a tantalum film, an intermediate layer of ruthenium film, a magnetic layer of a cobalt system, and a protective layer of a carbon protective film were formed on a plastic substrate by
20 a sputtering method. Table 5 gives the crystal structures, the spacings of the lattice planes that are essential for c-axis alignment control of the crystals of cobalt system, for Ta, Ru, and Co. The table also gives the misfits of spacings of lattice planes at the interface between the intermediate layer and the underlayer and at the

interface of the magnetic layer and the intermediate layer.

Table 5

	Ta underlayer	Ru intermediate layer	Co magnetic layer
lattice structure	bcc	hcp	hcp
essential lattice plane	(110)	(002)	(002)
spacing between lattice planes (Å)	2.338	2.142	2.023
misfit at interface (%)	8.4		5.6

5 The magnetic layer was contained by 20 at % of platinum, 10
at % of chromium, and 10 mol % of SiO₂ as a nonmetallic component,
with respect to the cobalt content. By the effect of the platinum
atoms contained at the interstices in the cobalt crystal lattice, the
spacing between (002) planes of the cobalt crystals becomes about
10 2.08 Å. Consequently, actual misfit at the interface between the
magnetic layer and the intermediate layer is supposed to be about
3 %.

15 The sputtering gas used was 100 % argon. The sputtering
conditions are shown in Table 6.

Table 6 Deposition conditions for each layer.

	underlayer	intermediate layer	magnetic layer
gas pressure (mTorr)	5	70	5
power (W)	570	440	700

The predetermined thickness and the value observed by a TEM for each layer are shown in Table 7. The samples were prepared by means of an ion milling method using PIPS Model 691. The TEM observation was conducted by a field emission transmission electron microscope, type JEM 2010F.

Table 7 Thickness of the layers.

	predetermined (nm)	TEM observation (nm)
magnetic layer	8	9.1
Ru intermediate layer	15	21.7
Ta underlayer	15	15.4

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A mean grain size in the planar direction and a standard deviation for each layer were obtained by TEM observation. The results are given in Table 8. The grain size analysis was executed by a dark field tracing method using an image analyzer, type Luzes-FS.

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Table 8

	mean grain size (nm)	standard deviation (nm)
magnetic layer	5.2	1.9
Ru intermediate layer	6.5	1.7
Ta underlayer	6.8	1.9

The mean grain size in the planar direction for every layer is smaller than respective layer thickness. An upper layer has a smaller grain size than a lower layer. The standard deviations are small, indicating almost uniform grain size. TEM image showed clear grain boundary and nearly uniform grain boundary region in the magnetic layer. The grain boundary can be considered to be generated by precipitation of SiO₂.

Example 2

Similar to the Example 1, sequentially formed were an underlayer of molybdenum film, an intermediate layer of ruthenium film, a magnetic layer of a film of cobalt system, and a protective layer of carbon protective film on a plastic substrate by a sputtering method.

The magnetic layer contained 20 at % of platinum, 10 at % of chromium, and 10 mol % of SiO₂ as a nonmetallic component, with

respect to the cobalt content.

Sputtering gas used was 100 % argon. The sputtering conditions were same as in Example 1.

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Comparative Examples

As comparative examples, magnetic recording media having layer constructions as shown in Table 9 were fabricated.

10 Table 9

	layer construction
Comp Example 1	substrate / Cr-16W / Mag
Comp Example 2	substrate / Cr-16W / Co-42Cr / Mag
Comp Example 3	substrate / Cr-16W / Co-42Cr / Ti-10Cr / Mag

In the Table 9, 'Mag' represents a magnetic layer. Comparative Example 1 comprises an underlayer of Cr-16W (Cr : W = 84 : 16) with a bcc structure, but lacks an intermediate layer. Comparative
15 Example 2 comprises an intermediate layer of Co-42Cr (Co : Cr = 58 : 42) with an hcp structure, but the spacing between (002) planes in this intermediate layer is smaller than the spacing between (002) planes in the magnetic layer. Comparative Example 3 comprises two
20 intermediate layers: first intermediate layer of Co-42Cr and second intermediate layer of Ti-10Cr (Ti : Cr = 90 : 10), but the spacing between (002) planes in the first intermediate layer is smaller than

the spacing between (002) planes in the second intermediate layer.

The magnetic recording media constructed as described above were subjected to measurements including coercive force H_c (Oe), product $B_r t$ (G μm) of remanent magnetic flux density B_r and thickness of the magnetic layer, product $B_s t$ (G μm) of saturation magnetic flux density B_s and thickness of the magnetic layer t , squareness ratio S ($= B_r / B_s$), and coercivity squareness ratio S^* (tangent at the coercive force on the magnetization curve).

The results of the measurements for these magnetic properties are given in Table 10.

Table 10

	H_c (Oe)	$B_r t$ (G μm)	S	S^*
Example 1	3,630	40	0.84	0.76
Example 2	3,570	40	0.89	0.73
Comp Example 1	2,010	60	0.86	0.80
Comp Example 2	2,840	70	0.94	0.77
Comp Example 3	2,380	50	0.82	0.67

As apparent from the table, the magnetic recording media of Examples 1 and 2 have exhibited superior magnetic properties as compared with the media of Comparative Examples.

The crystal structure, the principal crystal plane vertical to the

substrate surface, and the alignment of the crystal axis were studied by X-ray diffraction and electron diffraction by the TEM. The results are shown in Table 11.

5 Table 11

	crystal structure	principal plane	crystal axis alignment
magnetic layer	hcp	(002)	c-axis is horizontal
intermediate layer	hcp	(002)	c-axis is horizontal
Ta underlayer	bcc	(110)	nearly random

The crystal alignment of the c-axis to the horizontal direction was revealed stronger in the magnetic layer than in the intermediate layer.

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Advantageous Effect of the invention

As described so far, a magnetic recording medium of the present invention comprises a substrate, an underlayer with a body centered cubic structure formed on the substrate, an intermediated layer with
15 a hexagonal closest packed crystal structure formed on the underlayer, a magnetic layer composed principally of cobalt with the hexagonal closest packed structure formed on the intermediate layer, and a protective layer formed on the magnetic layer; and a relation $d_1 > d_2 > d_3$ holds, where d_1 is a spacing between (110) planes of the
20 underlayer; d_2 is a spacing between (002) planes of the intermediate

layer; and d_3 is a spacing between (002) planes in the magnetic layer.

A magnetic recording layer having this structure of the invention allows being produced without substrate heating steps in sputtering processes, and exhibits excellent magnetic performances.

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Claims

1. A magnetic recording medium comprising:
a substrate;
an underlayer with a body centered cubic crystal structure
5 formed on the substrate;
an intermediated layer with a hexagonal closest packed crystal structure formed on the underlayer;
a magnetic layer composed principally of cobalt with the hexagonal closest packed structure formed on the intermediate layer;
10 and
a protective layer formed on the magnetic layer;
wherein a relation $d_1 > d_2 > d_3$ holds, where d_1 is a spacing between (110) planes of the underlayer; d_2 is a spacing between (002) planes of the intermediate layer; and d_3 is a spacing between (002) planes in
15 the magnetic layer.
2. A magnetic recording medium according to claim 1, wherein further holds a relation $0.0 < (d_1 - d_2) / d_1 < 0.1$.
- 20 3. A magnetic recording medium according to claim 1, wherein further holds a relation $0.0 < (d_2 - d_3) / d_2 < 0.1$.
4. A magnetic recording medium according to claim 1, wherein simultaneously hold a relation $0.0 < (d_1 - d_2) / d_1 < 0.1$ and a relation

$$0.0 < (d_2 - d_3) / d_2 < 0.1.$$

5. A magnetic recording medium according to any one of claims 1 through 4, wherein a material of the magnetic layer contains a nonmetallic element or a nonmetallic compound in a proportion from 5 to 20 mol % with respect to content of the cobalt.

6. A magnetic recording medium according to any one of claims 1 through 4, wherein a material of the magnetic layer contains platinum in a proportion of 10 to 50 at % with respect to content of the cobalt.

7. A magnetic recording medium according to any one of claims 1 through 4, wherein a material of the magnetic layer contains a nonmetallic element or a nonmetallic compound in a proportion of 5 to 20 mol % with respect to a content of the cobalt and platinum in a proportion of 10 to 50 at % with respect to the content of the cobalt.

8. A magnetic recording medium according to any one of claims 1 through 7, wherein the intermediate layer is principally composed of Ru, Re, Os, or Tc.

9. A magnetic recording medium according to any one of claims 1 through 7, wherein the intermediate layer is principally composed of

an intermetallic compound selected from Rh_3W , Ni_3Sn , Ni_3Zr , and Co_3W .

10. A magnetic recording medium according to any one of claims 1
5 through 9, wherein the underlayer is principally composed of Ta, Nb, W, or Mo.

11. A magnetic recording medium according to any one of claims 1
through 10 further comprising a seed layer composed of an
10 intermetallic compound with a composition of CoTi, CoZr, CuZr, FeTi, or NiTi

12. A magnetic recording medium according to any one of claims 1
through 11, wherein a direction of magnetization for recording
15 information in the magnetic layer is horizontal in relation to the substrate.

13. A magnetic recording medium according to any one of claims 1
through 12, wherein at least one of the underlayer, the intermediate
20 layer, the magnetic layer, and the protective layer is formed by means of a sputtering method.

14. A magnetic recording medium according to any one of claims 1
through 13, wherein a thickness of the underlayer is in the range

from 5 to 20 nm.

15. A magnetic recording medium according to any one of claims 1 through 14, wherein a thickness of the intermediate layer is in the
5 range from 5 to 50 nm.

16. A magnetic recording medium according to any one of claims 1 through 15, wherein a thickness of the magnetic layer is in the range from 5 to 20 nm.

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17. A magnetic recording medium according to any one of claims 1 through 16, wherein the intermediate layer consists of a first intermediate layer with a hexagonal crystal structure formed on the underlayer and a second intermediate layer with a hexagonal crystal
15 structure formed between the first intermediate layer and the magnetic layer, and a relation $d_1 > d_4 > d_5 > d_3$ holds, where d_4 is a spacing between (002) planes of the first intermediate layer and d_5 is a spacing between (002) planes of the second intermediate layer.

20 18. A magnetic recording medium according to any one of claims 1 through 17, wherein the underlayer consists of a first underlayer with a body centered cubic crystal structure formed on the substrate and a second underlayer with a body centered cubic crystal structure formed between the first underlayer and the intermediate layer, and

a relation $d_6 > d_7 > d_2$ holds, where d_6 is a spacing between (110) planes in the first underlayer and d_7 is a spacing between (110) planes in the second underlayer.

5 19. A magnetic recording medium according to any one of claims 1 through 18, wherein further holds a relation $0.02 \leq (d_1 - d_2)/d_1$.

20. A magnetic recording medium according to any one of claims 1 through 18, wherein further holds a relation $0.02 \leq (d_2 - d_3)/d_2$.

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21. A magnetic recording medium according to any one of claims 1 through 18, wherein simultaneously hold a relation $0.02 \leq (d_1 - d_2)/d_1$ and a relation $0.02 \leq (d_2 - d_3)/d_2$.

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