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Magnetic Recording Medium

Technical field of the invention

The present invention relates in general to a magnetic recording
5 medium and in particular to a high performance and highly reliable
magnetic recording medium that exhibits low noise and sufficiently
high coercive force and is mounted on a variety of magnetic storage
devices such as an external storage device of a computer.

10 Background of the invention

A magnetic storage device is one of information recording devices
that support highly informational society in recent years. With
increase of information to vast amounts, magnetic recording media
used in magnetic storage devices are forced towards higher recording
15 density and lower noises. Achieving high recording density needs
minimization of a unit size of inversion of magnetization, which in
turn requires minute magnetic grain size. Lowering of noises needs
reduction of fluctuation of magnetization due to magnetic interaction
between grains in addition to the minute grain size.

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A magnetic layer using a CoCrPt alloy in a conventional medium
contains a great amount of chromium to segregate enough chromium
towards the grain boundary region for achieving noise reduction. As
a result, the magnetic anisotropy constant K_u of the magnetic grains



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is lowered, and the thermal stability of the medium deteriorates. On the other hand, if platinum content is increased aiming at enhancement of this K_u value, the chromium segregation to the grain boundary region is hindered, resulting in increase of media noise.

- 5 Thus, there exists a trade-off relation between the thermal stability and the noise reduction

To address these problems, a variety of proposals have been made including compositions and structures of a magnetic layer, and
10 materials for a nonmagnetic underlayer and a seed layer. Among them, a type of medium has been proposed having a so-called granular magnetic layer consisting of magnetic crystal grains and nonmagnetic matrix of an oxide or a nitride surrounding the crystal grains. In a medium having a granular structure, the magnetic
15 grains are nearly perfectly isolated magnetically from each other by virtue of the intervening nonmagnetic substance. Since the minimum magnetization unit can be the size of individual grain, which is 4 to 10 nm, high recording density is possible to at least this precise dimension. Besides, exchange interaction between the grains is
20 expected to be suppressed by the nonmagnetic matrix surrounding each grain.

The granular magnetic layer inherently allows avoiding addition of quantities of chromium because the grain boundary segregation is

principally performed by silicon oxide contrary to a conventional CoCrPt magnetic layer. Since the silicon oxide is compelled to precipitate at the grain boundary in the granular magnetic layer, the grain boundary segregation is promoted without lowering the magnetic anisotropy constant K_u , which means compatibility with noise reduction. For higher recording density in the future, it is indispensable to make the magnetic layer thinner. The thinner magnetic layer has lower magnetic anisotropy energy $K_u V$, where K_u : magnetic anisotropy constant and V : activation volume. To prevent lowering of the magnetic anisotropy energy, the magnetic anisotropy constant K_u must be increased, which requires addition of more amount of platinum to the composition of the magnetic layer. Although addition of large amounts of platinum inhibits the grain boundary segregation of chromium in a conventional CoCrPt magnetic layer and increases noises, in a granular magnetic layer, in contrast, since silicon oxide easily segregate to the grain boundary region even if plenty of platinum is added, the granular magnetic layer has the advantage that larger amount of platinum can be contained while maintaining isolation of magnetic grains.

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United States Patent No. 5,679,473, for example, discloses that low noise is achieved by a granular recording film having a structure in which each magnetic crystal grain is separated by nonmagnetic oxide surrounding the grain. The granular recording film in the

reference can be formed by deposition employing RF sputtering using a target of CoNiPt with an additive of an oxide such as SiO₂. In such a granular magnetic film, since a nonmagnetic and nonmetallic phase physically separates each magnetic grain, magnetic interaction
5 between the magnetic grains diminishes. So the formation of zigzag magnetic domain wall is suppressed that arises at a transition region of a recording bit, leading to achieving low noise characteristic.

Japanese Unexamined Patent Application Publication Nos. H11-
10 213371 and 2000-123445 disclose depositing an underlayer with body centered cubic structure prior to depositing the magnetic layer that has a hexagonal closest packed structure. Japanese Unexamined Patent Application Publication No. 2000-82210 discloses a magnetic recording medium provided with a nonmagnetic intermediate layer
15 with body centered cubic structure between the magnetic layer and the underlayer.

Problem to be solved by the invention

In order to accomplish a medium with excellent electromagnetic
20 conversion characteristic using a granular magnetic layer, the oxide such as SiO₂ and the cobalt alloy that are contained in the target need to be well separated in the deposited magnetic film. It is also important to make the size of the magnetic grain homogeneous to reduce noises.

When the platinum content in the granular magnetic layer is increased to cope with further high density recording in the future, degradation of lattice matching is anticipated due to increase of an amount of misfit between a conventional CoCr alloy intermediate
5 layer and the magnetic layer because the lattice constants of the CoCrPt alloy of the magnetic layer increase in proportion only to the platinum content.

Indeed low noise may be achieved by the structure in which the
10 nonmagnetic and nonmetallic grain boundary region separates the magnetic grains. Nevertheless, if a nonmagnetic intermediate layer is deposited using a material with hexagonal closest packed or body centered cubic structure that has a spacing of lattice planes different from that of the crystal grains in the magnetic layer by a relative
15 proportion over 15 %, the grain size of the magnetic grains in the magnetic layer cannot be controlled without difficulty by depositing the magnetic layer on such a nonmagnetic intermediate layer because of inferior lattice matching between the crystal grains in the intermediate layer and the crystal grains in the magnetic layer. That
20 is, to accomplish further low noise in a magnetic recording medium, it is required to precisely control minute and uniform grain size of the magnetic crystal grains in the intermediate layer.

The present invention has been made in view of this problem,

and an object of the invention is to provide a magnetic recording medium with low noise and high coercive force. By controlling the structure and the grain size distribution of a nonmagnetic intermediate layer, the structure and the grain size of the crystal grain in a magnetic layer deposited on the intermediate layer are controlled, to achieve low noise. By controlling the structure and the grain size distribution of the intermediate layer, the distance between the crystal grains in the magnetic film is controlled and the interaction between the magnetic crystal grains is diminished, which leads to high coercive force even in the case of minute grain size of the magnetic crystal grains in the magnetic layer.

The inventors of the present invention have studied in detail the noise reduction by means of grain size control of the granular magnetic layer and found the following fact. When a magnetic layer is deposited on a crystalline nonmagnetic intermediate layer with hexagonal closest packed structure, which is the same as that of the ferromagnetic crystal grains in the magnetic layer, each cobalt grain in the magnetic layer grows corresponding to the crystalline grain in the intermediate layer, and the oxide in the magnetic layer segregates and grows corresponding to the amorphous region or a porous region around the grain boundary of the crystal grain in the intermediate layer. The grain size of the crystal grains in the magnetic layer has been demonstrated possible to be controlled by

controlling the grain size of the crystal grains of the intermediate layer on which the magnetic layer grows. Thus, excellent magnetic performances can be achieved. In other words, magnetic crystal grains epitaxially grow on the crystal grains in the nonmagnetic intermediate layer made by a sputtering method. As a result, the crystal alignment of the nonmagnetic intermediate layer is followed by the magnetic layer to control the crystal alignment of the magnetic layer and, at the same time, to form an amorphous grain boundary region around the crystal grains in the magnetic layer. Thus, crystal structure of the magnetic layer having granular structure can be controlled.

Means to solve the problem

To accomplish the above object, a magnetic recording medium according to the present invention comprises a nonmagnetic underlayer, a magnetic layer, a protective layer, and a lubricant film sequentially laminated on a substrate. The magnetic layer has a granular structure consisting of ferromagnetic crystal grains with hexagonal closest packed structure and nonmagnetic grain boundary region of mainly oxide intervening between the ferromagnetic crystal grains. The underlayer has body centered cubic structure.

Advantageously, a magnetic recording medium of the invention

further comprises a nonmagnetic intermediate layer with hexagonal closest packed structure disposed between the magnetic layer and the underlayer. The intermediate layer is composed of a nonmagnetic metal mainly composed of one or more element selected from a group consisting of Ru, Os, and Re, wherein a degree of mismatching $\Delta = |d_1 - d_2|/d_1$ is at most 10 %, preferably in the range from 2.5 % to 7.0 %, where d_1 is a spacing of lattice planes of crystal grains included in the magnetic layer and d_2 is a spacing of lattice planes of crystal grains included in the nonmagnetic intermediate layer.

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Advantageously, a proportion of crystal grains with grain size of not smaller than 8 nm is at most 10 % of crystal grains included in the intermediate layer and a standard deviation of the grain size is at most 1.4 nm. Here, every “standard deviation” in the present application document is the square root of the unbiased variance.

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Advantageously, the substrate is not subjected to intentional heating prior to steps of depositing the layers.

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The substrate is preferably a resin substrate.

Brief description of drawings

Figure 1 is a schematic cross-sectional view of an example of

embodiment of a magnetic recording medium according to the present invention.

Figure 2 is a planar TEM image of a magnetic layer of the magnetic
5 recording medium of Example 4.

Figure 3 is a graph showing the grain size distribution of the
nonmagnetic intermediate layer and a magnetic layer of the magnetic
recording medium of Example 4.
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Figure 4 is a cross sectional TEM image of the nonmagnetic
intermediate layer and a magnetic layer of the magnetic recording
medium of Example 4.

15 Figure 5 is a graph showing the grain size distribution of the
nonmagnetic intermediate layer and a magnetic layer of the magnetic
recording medium of Example 5.

Aspects of embodiments of the invention

20 Aspects of embodiments of the present invention will be
described with reference to the accompanying drawings.

Example 1

Figure 1 is a drawing illustrating an example of construction of a

magnetic recording medium according to the present invention. Sequentially laminated on a substrate 1 are an underlayer 2, a nonmagnetic intermediate layer 3, a magnetic layer 4, a protective layer 5, and a lubricant film 6.

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The substrate 1 in this example is a 3.5 inch diameter disk of polyolefin resin with a smooth surface. After cleaning, the substrate was introduced into a sputtering apparatus and an underlayer 2 with body centered cubic structure was deposited by means of a DC sputtering method.

A nonmagnetic intermediate layer 3 having the thickness of 20 nm was formed on the underlayer 2 by the DC sputtering method at the deposition rate of 2.3 nm/sec under the discharge argon gas pressure of 30 mTorr. Subsequently, a granular magnetic layer 4 having thickness of 10 nm was formed by means of an RF sputtering method using a target of $\text{Co}_{76}\text{Cr}_{12}\text{Pt}_{12}$ added by 10 mol % of SiO_2 under the discharge argon gas pressure of 15 mTorr. After depositing a carbon protective layer 5 having the thickness of 8 nm, the laminated substrate was taken out from the vacuum chamber of the sputtering apparatus. Then, a liquid lubricant was applied to form a lubricant film 6 having thickness of 1.5 nm. The compositions of the nonmagnetic intermediate layer 3 were Ti-30 at% Cr, Co-35 at% Cr, Os, Re, and Ru. Heating of the substrate 1 before depositing the

intermediate layer 3 was not executed.

The thus produced magnetic recording media were subjected to measurements including coercive force H_c using a vibrating sample magnetometer VSM and reading and recording performance using a GMR head on a spinning stand tester. Signal to noise ratio SNR was evaluated at a linear recording density of 270 kFCI. Some of the test results are shown in Table 1.

Table 1

intermediate layer material	magnetic layer composition	H_c (Oe)	grain size (nm)	grain size deviation (*)	SNR (dB)	degree of mismatching (%)
Ru	$\text{Co}_{76}\text{Cr}_{12}\text{Pt}_{12}\cdot$ 10at%SiO ₂	3,500	6	0.2	19.0	4.8
Re	same as above	3,600	7	0.2	18.8	6.9
Ti ₇₀ Cr ₃₀	same as above	2,800	11	0.4	16.2	14.4
Co ₆₅ Cr ₃₅	same as above	3,300	9	0.3	14.1	2.8
Ru	$\text{Co}_{72}\text{Cr}_{12}\text{Pt}_{16}\cdot$ 10at%SiO ₂	3,850	6	0.2	21.2	3.9
Re	same as above	3,910	7	0.2	20.7	6.0
Ti ₇₀ Cr ₃₀	same as above	3,050	12	0.4	16.8	13.3
Co ₆₅ Cr ₃₅	same as above	3,550	9	0.3	14.7	3.7
Ru	$\text{Co}_{68}\text{Cr}_{12}\text{Pt}_{20}\cdot$ 10at%SiO ₂	4,210	6	0.2	23.4	2.7
Re	same as above	4,350	7	0.2	23.1	4.8
Ti ₇₀ Cr ₃₀	same as above	3,340	11	0.4	17.3	12.1
Co ₆₅ Cr ₃₅	same as above	3,820	10	0.3	15.5	4.8

(*) standard deviation of grain size divided by mean value of the grain size

In the case of the intermediate layer material of TiCr alloy, the degree of mismatching is larger than 12 %. Consequently, epitaxial growth of the magnetic layer from the intermediate layer is inhibited, and the grain size and its deviation in the magnetic layer are large.

5 As a result, the performances H_c and SNR are inferior to the case of the intermediate layer of ruthenium and the intermediate layer of rhenium. As for the case of the intermediate layer of CoCr alloy, the grain size of the magnetic crystal grains is large because the deposition process for the material accompanies difficulty in

10 generating fine grains, although the degree of mismatching is smaller than the case of the intermediate layer of ruthenium or rhenium. As a result, the SNR is inferior much than the cases of the ruthenium intermediate layer and the rhenium intermediate layer. It has been demonstrated that the H_c and the SNR are significantly improved

15 with a nonmagnetic intermediate layer made of Re, Os, or Ru, wherein a degree of mismatching $\Delta = |d_1 - d_2|/d_1$ is at most 10 %, preferably in the range from 2.5 % to 7.0 %, where d_1 is a spacing of lattice planes of crystal grains included in the magnetic layer 4 and d_2 is a spacing of lattice planes of crystal grains included in the

20 nonmagnetic intermediate layer 3.

Example 2

In this example, an underlayer was deposited by a sputtering method for controlling the grain size of the crystal grains in the

nonmagnetic intermediate layer shown in Figure 1. A nonmagnetic intermediate layer was deposited on the underlayer. The material for the intermediate layer was limited to ruthenium in this example.

Lamination of the intermediate layer was executed at the two

5 deposition rates: 1.1 nm/sec and 2.3 nm/sec. The other conditions are the same as those described in Example 1.

Ruthenium was used for the material of the intermediate layer.

The intermediate layer 20 nm thick was deposited by means of a DC
10 sputtering method at the deposition rate of 2.3 nm/sec under the discharging argon gas pressure of 70 mTorr. Observation of the cross section of the intermediate layer by TEM revealed a porous structure including columnar crystals perpendicular to the substrate surface.

The columnar crystals were confirmed grown without abnormal
15 growth in which the crystal grains expand in the course of the growth, for example. So-called "initial growth layer" was not observed around the interface between the underlayer and the intermediate layer.

Grain size was determined by planar observation by the TEM. The mean grain size was about 6 nm. The distribution of the grain sizes
20 was a normal distribution, and the standard deviation was 1.8 nm.

For the purpose of making the grain size in an intermediate layer smaller, an intermediate layer 20 nm thick was formed at the depositing rate of 1.1 nm/sec under discharging argon gas pressure of

70 mTorr. Observation of the cross section of the thus obtained intermediate layer by the TEM showed a porous structure including columnar crystals perpendicular to the substrate surface. These columnar crystals were confirmed grown without abnormal growth in which the crystal grains expand in the course of the growth. An initial growth layer was not observed around the interface between the underlayer and the intermediate layer. Grain size was determined by planar observation by the TEM to give a grain size of about 5 nm. The distribution of the grain sizes was a normal distribution, and the standard deviation was 1.4 nm.

Dependence of crystal alignment on the deposition rate was studied by in-plane X-ray diffraction analysis about the crystal structure of the intermediate layers that were deposited fixing the conditions other than the deposition rate. In addition to an intense peak of ruthenium (002) at around $2\theta = 18^\circ$, weak peaks of ruthenium (100) and ruthenium (101) at around $2\theta = 17^\circ$ and $2\theta = 19^\circ$, respectively, were observed. Analyzing this result together with the above-described TEM observation, it was indicated that the ruthenium c-axis was predominantly aligned in-plane. It has been confirmed that the control of the grain size and its distribution is possible while preserving the crystal alignment by controlling the deposition rate.

Example 3

In this example, an underlayer was deposited by a sputtering method for controlling the grain size of the crystal grains in the nonmagnetic intermediate layer shown in Figure 1. A nonmagnetic intermediate layer was deposited on the underlayer. The other conditions are the same as those described in Example 1. Ruthenium was used for the material of the nonmagnetic intermediate layer. Intermediate layers having various thicknesses were deposited by means of a DC sputtering method at the deposition rate of 2.3 nm/sec under the discharging argon gas pressure of 70 mTorr. The other conditions are the same as those described in Example 1.

Planar TEM observations were made on a relatively thin intermediate layer 10 nm thick and a relatively thick intermediate layer 50 nm thick. The grain sizes of the two intermediate layers were determined by image analysis based on the TEM observation, to give the mean grain sizes of 6 nm and 8 nm, respectively. The distribution of the grain sizes was a normal distribution, and the values of the standard deviation were 1.4 nm and 2.2 nm, respectively. Observation of the cross section of each of these intermediate layers by the TEM revealed columnar structure in the both films. An initial growth layer was not observed around the interface between the underlayer and the intermediate layer.

Further in this example, an underlayer was deposited by a sputtering method for controlling the grain size of the crystal grains in the nonmagnetic intermediate layer shown in Figure 1. A nonmagnetic intermediate layer was deposited on the underlayer.

5 Ruthenium was used for the material of the intermediate layer. Intermediate layers having the fixed thickness of 20 nm were deposited by means of the DC sputtering method at the deposition rate of 2.3 nm/sec under the discharging argon gas pressure of 49 mTorr, which is 0.7 times above-mentioned 70 mTorr and 84 mTorr,

10 which is 1.2 times the 70 mTorr. The other conditions were the same as those described in Example 1.

Planar TEM observation was made on the thus deposited intermediate layers. The grain sizes were determined by image

15 analysis based on the TEM observation, to give the mean grain sizes of 8 nm and 5 nm, respectively. The distribution of the grain sizes was a normal distribution, and the values of the standard deviation were 2.4 nm and 1.9 nm, respectively. Observation of the cross section of each of these intermediate layers by the TEM revealed

20 columnar structure in the both films. An initial growth layer was not observed around the interface between the underlayer and the intermediate layer.

Crystal alignment of these intermediate layers was analyzed by

means of an in-plane X-ray diffraction method and TEM observation, and the predominant in-plane alignment of the ruthenium c-axis was certified. Although significant difference was not observed in the crystal alignment between the different deposition conditions, a thick
5 intermediate layer caused larger scatter in the crystal grain size due to lattice defects and crystal growth. It was confirmed that when the argon gas pressure was low, the grain boundary region between the crystal grains was narrow because the grain size was large and the film was dense.

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As described above, it has been demonstrated that the grain size of the crystal grain and structure of the nonmagnetic intermediate layer can be controlled by the thickness of the intermediate layer and the argon gas pressure during the deposition process of the
15 intermediate layer. When the thickness of the intermediate layer is thinner than 5 nm, stable deposition is difficult because of the construction of the deposition apparatus. When thicker than 100 nm, the manufacturing process is imposed by a restriction of requirement for a long deposition time.

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Example 4

In this example, a magnetic recording medium was produced by depositing a magnetic layer of a cobalt alloy on a nonmagnetic intermediate layer deposited under the conditions described for the

Example 2. Namely, ruthenium for a nonmagnetic intermediate layer 20 nm thick was deposited at the deposition rate of 2.3 nm/sec under the discharge argon gas pressure of 70 mTorr. On this intermediated layer, a granular magnetic layer 10 nm thick was deposited by means of an RF sputtering method using a target of $\text{Co}_{76}\text{Cr}_{12}\text{Pt}_{12}$ containing 10 mol% of SiO_2 under a discharge argon gas pressure of 15 mTorr. After laminating a carbon protective layer 8 nm thick, the laminated substrate was taken out from the vacuum chamber. Then, liquid lubricant was applied to the thickness of 1.5 nm to form a lubricant film. Thus, a magnetic recording medium having the structure as shown in Figure 1 was produced. Substrate heating was not conducted prior to these deposition steps.

Figure 2 is a picture of the structure of the magnetic layer of the thus obtained magnetic recording medium taken by planar TEM. The magnetic layer has been certified having a granular structure consisting of the magnetic crystal grains and the region of nonmagnetic phase surrounding the grains. The observation of a lattice image of the grain boundary region under a high resolution condition has revealed that the cobalt alloy grain was crystalline and the grain boundary region was amorphous. The mean distance between the crystal grains was 1.1 nm and its standard deviation was 2.0 nm. Grain size measurement resulted in the mean grain size of 4.9 nm.

Figure 3 is a graph illustrating the grain size distribution of the ruthenium intermediate layer and the magnetic layer in the magnetic recording medium of this example. The distribution of the grain size in the magnetic layer showed two peaks at around the grain sizes of 4 nm and 8 nm. Its deviation defined by the standard deviation divided by the mean grain size was 0.4.

Figure 4 is a picture of the cross section of the magnetic film obtained by the TEM observation. Continuation of the crystal lattice was observed between the intermediate layer and the magnetic layer, and the crystal grains in the magnetic layer was shown epitaxially growing from the interface with the intermediate layer. The crystalline phase of the cobalt alloy and the amorphous phase of the grain boundary region were different in the growth mechanism of the magnetic film and had the different respective metallographic structure. An in-plane X-ray diffraction showed an intense peak of cobalt (002) at around $2\theta = 19^\circ$. Considering the result of X-ray diffraction by a θ - 2θ method together with the result of the TEM observation, predominant alignment of cobalt (100) was known.

Magnetic properties of this magnetic layer were measured by a vibrating sample magnetometer (VSM). Coercive force was 2.9 kOe, and indices of squareness of an M-H hysteresis loop: the squareness ratio S and the coercivity squareness ratio S* were both 0.8. Thus,

good magnetic performances have been demonstrated. Such squareness of the hysteresis loop has been resulted from reduction in the interactions between magnetic crystal grains in the magnetic layer; the reduction is produced because the growth mechanism of the magnetic layer is different from the previous one due to the formation of the nonmagnetic grain boundary region.

Example 5

In this example, an underlayer was deposited by a sputtering method for controlling the grain size of the crystal grains in the nonmagnetic intermediate layer shown in Figure 1. An intermediate layer was deposited on the underlayer. Ruthenium was used for a material of the nonmagnetic intermediate layer. Intermediate layers having various thicknesses were deposited by means of a DC sputtering method at the deposition rate of 1.1 nm/sec under the discharge argon gas pressure of 70 mTorr. Magnetic recording medium were produced under the deposition and other conditions that were the same as those described for the Example 1. Substrate heating prior to the deposition processes was not conducted.

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The thus obtained magnetic layer was observed by the planar TEM. A granular structure of the magnetic layer was confirmed in which crystal grains were surrounded by a nonmagnetic phase region. The observation of a lattice image under a high resolution condition

has revealed that the cobalt alloy crystal grain was crystalline and the grain boundary region was amorphous. The mean distance between the crystal grains was 1.5 nm and its standard deviation was 1.4 nm. Grain size measurement resulted in the mean grain size of
5 4.0 nm.

Figure 5 is a graph illustrating the grain size distribution of the ruthenium nonmagnetic intermediate layer and the magnetic layer in the magnetic recording medium of this example. The distribution of
10 the grain size in the magnetic layer showed a peak at around the grain size of 6 nm, and its deviation defined by the standard deviation divided by the mean grain size was 0.2.

The cross sectional structure of this film was observed by the
15 TEM. Continuation of the lattice was observed between the intermediate layer and the magnetic layer, and the crystal grains in the magnetic layer was shown epitaxially growing from the interface with the intermediate layer. The crystalline phase and the grain boundary phase in the magnetic layer were different in the growth
20 mechanism and had the different respective metallographic structure. An in-plane X-ray diffraction showed an intense peak of cobalt (002) at around $2\theta = 19^\circ$. Considering the result of X-ray diffraction by a $\theta - 2\theta$ method together with the result of the TEM observation, predominant alignment of cobalt (100) was known.

Magnetic properties of this magnetic layer were measured by the VSM. The coercive force was 3.5 kOe, and the indices of squareness of the M-H hysteresis loop: the squareness ratio S and the coercivity squareness ratio S^* were 0.9 and 0.8, respectively. Thus, excellent
5 magnetic performances were demonstrated. Such squareness of the hysteresis loop has been resulted, on the one hand, from the normal distribution of the grain size, and on the other hand, from reduction of the interactions between magnetic crystal grains, the reduction being produced because the growth mechanism of the magnetic layer
10 is different from the previous one due to the existence of the grain boundary region of the intermediate layer.

Example 6

Table 2 summarizes the evaluation results for the recording
15 performances of the magnetic disk using the magnetic film having the magnetic characteristics shown in Example 4 and Example 5. The recording performances were measured by a spinning stand tester equipped with a GMR head, and the reproduced output of an isolated read back pulse was evaluated at the linear recording density of 160
20 kFCI.

Table 2

sample	overwrite (dB)	TAA (*) (mV)	noise (μ V)	SNR (dB)
Example 4	46.4	0.98	81.8	15.6
Example 5	43.7	0.94	53.0	19.0

(*) track average amplitude

5 The magnetic recording medium of Example 5 exhibited reduction in noises by 35 % and improvement in SNR by 16 % as compared with the magnetic recording medium of Example 4. As shown in the results of the grain size analysis of the magnetic layer, the proportion of the crystal grains in the nonmagnetic intermediate
10 layer having the grain size exceeding 8 nm was controlled from 40 %, which is the data of Example 4 shown in Fig. 3, to 10 %, which is the data of Example 5 shown in Fig. 5, and as a result, the proportion of crystal grains in the magnetic layer having the grain size below 4 nm was reduced from 15 % to 5 %, and the deviation, which is the
15 standard deviation divided by the mean grain size, was controlled to be 0.2. Through these effects, the remarkable reduction of noises and improvement of SNR have been achieved. The magnetic layer of Example 5 was laminated on the intermediate layer having the standard deviation of the grain size of 1.4 nm. Thus, it has been
20 demonstrated that the standard deviation of grain sizes of an intermediate layer is preferably 1.4 nm or smaller.

A crystal grain in the nonmagnetic intermediate layer having a grain size of larger than 8 nm acts to separate the magnetic grain growing on the crystal grain, and hinders control of the grain size and its deviation of the crystal grains in the magnetic layer, and prevents control of the grain boundary segregation of the metal element in the magnetic layer. Accordingly, when the proportion of the crystal grains in the intermediate layer having a grain size over 8 nm is decreased to within 10 %, the proportion of the crystal grains in the magnetic layer that have one to one correspondence to a crystal grain in the intermediate layer increases. That is attributed to the above-mentioned reduction in noises and improvement in the SNR. Such crystal growth promotes precise lattice matching to improve lattice matching at the interface between the magnetic layer and the intermediate layer, and also promotes the segregation structure by the aid of the columnar porous structure in the intermediate layer. Hence, excellent electromagnetic conversion characteristics can be achieved.

Advantageous Effect of the invention

An magnetic recording medium according to the present invention is provided with a nonmagnetic intermediate layer with hexagonal closest packed structure mainly composed of at least one element selected from Ru, Os, and Re between a magnetic layer and an underlayer, wherein a degree of mismatching $\Delta = |d_1 - d_2| / d_1$ is at

most 10 %, preferably in the range from 2.5 % to 7.0 %, where d_1 is a spacing of lattice planes of crystal grains in the magnetic layer and d_2 is a spacing of lattice planes of crystal grains in the intermediate layer. By virtue of this featured structure, a magnetic recording
5 medium exhibiting reduced noises and excellent magnetic performance and electromagnetic conversion characteristics can be provided.

In addition, by controlling the distance between the crystal
10 grains in the magnetic layer, the interaction between the magnetic crystal grains can be decreased. Since even in the case of minimized grain size in the magnetic layer, sufficiently high coercive force is held at the room temperature, stable high density recording can be accomplished with little effect of thermal disturbance.

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Claims

1. A magnetic recording medium comprising a substrate and layers sequentially laminated on said substrate said layers including a
5 nonmagnetic underlayer, a magnetic layer, a protective layer, and a lubricant film, wherein said magnetic layer has a granular structure consisting of ferromagnetic crystal grains with hexagonal closest packed structure and nonmagnetic grain boundary region of mainly oxide intervening between said crystal grains, and said underlayer
10 has body-centered cubic lattice structure.
2. A magnetic recording medium according to claim 1, wherein said ferromagnetic crystal grains contain from 12 at% to 20 at% of platinum.
- 15 3. A magnetic recording medium according to claim 1 further comprising a nonmagnetic intermediate layer with hexagonal closest packed structure disposed between said magnetic layer and said underlayer, said nonmagnetic intermediate layer being a
20 nonmagnetic metal mainly composed of one or more element selected from a group consisting of Ru, Os, and Re, wherein a degree of mismatching $\Delta = |d_1 - d_2|/d_1$ is at most 10 %, where d_1 is a spacing of lattice planes of crystal grains included in said magnetic layer and d_2 is a spacing of lattice planes of crystal grains included in said

intermediate layer.

4. A magnetic recording medium according to claim 3, wherein said degree of mismatching Δ is in the range from 2.5 % to 7.0 %.

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5. A magnetic recording medium according to claim 2, wherein a proportion of crystal grains with grain size of not smaller than 8 nm is at most 10 % of crystal grains included in said intermediate layer and a standard deviation of said grain size is at most 1.4 nm.

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6. A magnetic recording medium according to any one of claims 1 through 3, wherein said substrate is not subjected to intentional heating prior to steps of depositing said layers.

15 7. A magnetic recording medium according to any one of claims 1 through 4, wherein said substrate is a resin substrate.

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