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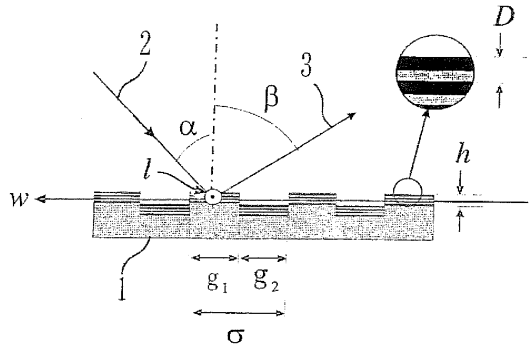
(54) MULTI-LAYER FILM TYPE DIFFRACTION GRATING

(57) If a multilayer film is to be formed on the surface of a laminar-type diffraction grating with a view to increasing the diffraction efficiency, it is necessary to satisfy the four conditions, (1) conditions such as the groove depth at which a maximum reflectance is attained, (2) an extended Bragg condition for the multilayer film, (3) the conditional equation that specifies the correlation between the directions of incident light and diffracted light, and (4) the ratio between the widths of a land and a valley in the surface of the laminar-type diffraction grating; however, there have been available no unified design guidelines. The present invention has been accomplished in order to solve this problem and it provides not only comprehensive design guidelines but also optimum materials pairs for use in the multilayer film; its object is to provide a diffraction grating having high diffraction efficiency and high resolution in a wavelength region of 0.1-1 nm, where conventional diffraction gratings suffer their extremely low diffraction efficiency and it makes hard to separate into spectral components from a polychromatic light.

Fig. 1



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Description

TECHNICAL FIELD

[0001] The present invention relates to multilayer diffraction gratings that may be used to generate monochromatic light in the soft X-ray region or disperse the incident light by wavelength. More particularly, the present invention provides multilayer diffraction gratings having high diffraction efficiency and resolution in a wavelength region of 0.1-1 nm, where conventional diffraction gratings suffer their extremely low diffraction efficiency and it makes hard to separate into spectral components from a polychromatic light.

BACKGROUND ART

[0002] Forming a multilayer as a means of increasing the reflectance of a reflector is a practice that is more than half a century old. If this means is to be employed in order to increase diffraction efficiency of a diffraction grating, various conditions have to be satisfied and generally diffraction gratings are hardly practicable if they are to be used in the soft X-ray region.

[0003] Laminar-type diffraction gratings are generally required to satisfy certain conditions in order to attain a maximum efficiency in terms of the depth of grooves in the laminar-type diffraction grating (see FIG. 1) or the ratio (called duty ratio) between the width of a ridge (land) and the grating constant (groove interval at the center of the diffraction grating); in addition, if a multilayer film is to be formed on the surface of the laminar-type diffraction grating with a view to increasing the diffraction efficiency, the multilayer should satisfy an extended Bragg condition (see, for example, Nonpatent Documents 1 and 2).

[0004] These four conditions have been studied individually but no unified and systematic guidelines have been shown in a so-called grazing-incidence region where a angle of incidence as measured from the surface normal is 80 degrees or more. NONPATENT DOCUMENT 1: W. K. Warburton, Nucl. Instr. Meth. A 291, 278 (1990).
NONPATENT DOCUMENT 2: M. Koike and K. Sano, "The Fifth Series of Experimental Chemistry, Vol. 10, Spectroscopy and Diffraction II", Maruzen (2005), Chapter 2, Section 3, p. 106-141.

DISCLOSURE OF THE INVENTION

PROBLEMS TO BE SOLVED BY THE INVENTION

[0005] The present invention has been accomplished in order to solve those problems and its object is to provide diffraction gratings having high diffraction efficiency and resolution in a wavelength region of 0.1-1 nm where separating incident polylchromatic light by diffraction gratings into its spectral components (generate monochromatic light or dispersing the incident light by wavelength) has been difficult due to their extreme low efficiency, as well as to provide a spectroscopic apparatus using these diffraction gratings.

MEANS FOR SOLVING THE PROBLEMS

[0006] The present invention has been accomplished in order to solve the aforementioned problems and it comprises the conditions of a wavelength scanning mechanism and diffraction gratings in a spectroscopic apparatus that satisfy the following four conditions simultaneously regardless its scanning wavelength.

[0007] The four conditions are: (1) the condition to be satisfied by a diffraction grating in terms of a relation that specifies the correlation between each of the directions of incident light and diffracted light, and the grating constant; (2) the condition to be satisfied by the ratio (called duty ratio) between the width of a land (ridge) on a laminar-type diffraction grating and the diffraction grating constant, at which a maximum efficiency is attained; (3) the condition to be satisfied by the groove depth of the laminar-type diffraction grating, at which a maximum efficiency is attained; and (4) an extended Bragg condition for a multilayer film. Among these conditions, (1) and (4) shall assume the conditions described in Nonpatent Document 1 and on the basis of these conditions, one may design a diffraction grating of a groove shape that has a duty ratio and a groove depth which satisfy conditions (2) and (3).

[0008] In short, writing λ for the wavelength of incident light, α for the angle of incidence measured from the surface normal, β for the angle of diffraction of the diffracted light also measured from the same normal line, σ for the interval between grooves in the diffraction grating, n for the average refractive index of a multilayer film (δ = n-1), m_G for the diffraction order of the diffraction grating, m_C for the interference order of the multilayer, h for the depth of grooves, g_1 for the width of a land, and g_2 for the width of a valley, the present invention is a multilayer diffraction grating that satisfies the following four conditions:

1) the formula of the diffraction grating, expressed by the following equation (1), that specifies the correlation between each of the directions of incident light and diffracted light and the diffraction grating constant:

[0009]

[Formula 1]

$$m_G\lambda = \sigma(\sin\alpha + \sin\beta) \qquad (1)$$

[0010] 2) an extended Bragg condition for the multilayer diffraction grating that is expressed by the following equation (2):

[0011]

[Formula 2]

$$m_C\lambda = D(R_\alpha\cos\alpha + R_\beta\cos\beta) \qquad (2)$$

[0012]

[Formula 3]

$$R_\alpha = \sqrt{1-(2\delta-\delta^2)/\cos^2\alpha}, \qquad (3a)$$

$$R_\beta = \sqrt{1-(2\delta-\delta^2)/\cos^2\beta}, \qquad (3b)$$

[0013] and, in addition to the conditions 1) and 2), 3) the condition, expressed by the following equation (4), for the groove depth of the multilayer film coated diffraction grating, at which a maximum diffraction efficiency is attained:

[0014]

[Formula 4]

$$h = \lambda/4\cos\alpha \qquad (4)$$

[0015] 4) the condition, expressed by the following equation (5), for the ratio (duty ratio, or D.R.) between the width of a land on the multilayer diffraction grating and the diffraction grating constant, at which a maximum diffraction efficiency is attained:

[0016]

[Formula 5]

$$D.R. = \frac{g_1}{\sigma} = \frac{g_2 - h(\tan\alpha - \tan\beta)}{\sigma}, \qquad (5)$$

[0017] further characterized in that the multilayer consists of a pair of two materials, each materials pair consisting of cobalt and silicon dioxide, cobalt and silicon carbide, or cobalt and carbon.

[0018] It should also be noted that the above-described laminar-type diffraction grating can be realized, including the control over the duty ratio and unequal groove intervals, by the holographic process in which interference fringes are recorded on a photoresist coated diffraction grating's substrate by means of two coherent laser beams; furthermore, the multilayer film to be added to the resulting laminar-type diffraction grating can be realized by forming, for example, alternating vapor deposited tungsten and carbon layers by ion-beam sputtering method, magnetron sputtering method, or a like method.

[0019] In addition to its use as the diffraction grating, the present invention can also be used as a reflector having its surface coated with a multilayer film consisting of materials pairs, which is operated in such a way that light with a wavelength up to 2 nm but not shorter than 0.1 nm is incident at an angle of at least 80 degrees as measured from the surface normal.

EFFECTS OF THE INVENTION

[0020] The diffraction grating according to the present invention and the spectroscopic apparatus having high diffraction efficiency and high resolution in the wavelength range of 0.1-2 nm, to thereby enable the measurement of very weak light in the wavelength region. In addition, the multilayer can get rid of the decrease in reflectance that has occurred when light is incident at small angle on a monolayer metal film and, therefore, in the case of receiving light of the same flux width, the diffraction grating can be made less wide depending on the direction of ruling (perpendicular to the direction in which the grooves of the diffraction grating extend; namely, left and right sides of FIG. 1). The term "resolution" as used hereinabove means the value defined by the wavelength divided by the spectral (wavelength) width that can be distinguished by the spectroscope apparatus and the large value means, the higher the performance of resolution by wavelength.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021]

[FIG. 1] FIG. 1 is a schematic diagram showing a laminar-type multilayer film coated planar diffraction grating.
[FIG. 2] FIG. 2 is a table showing the principal parameters of the laminar-type multilayer film coated planar diffraction grating according to an Example of the present invention.
[FIG. 3] FIG. 3 is a graph showing the diffraction efficiency of the laminar-type multilayer film coated plane diffraction grating according to the Example of the present invention.

LEGEND

[0022]

1: laminar-type multilayer film coated plane diffraction grating
2: incident light
3: diffracted light

BEST MODE FOR CARRYING OUT THE INVENTION

[0023] In the present invention, a pattern of grooves for a multilayer film coated diffraction grating is formed by the holographic method using laser light; then, with the resulting pattern used as a mask, laminar-type grooves are formed by ion-beam etching. In the next step, a multilayer film is deposited on the grooved surface by ion-beam sputtering method or magnetron sputtering method.

[0024] The zeroth-order light is referred to in accompanying claim 1 and this means the following: a diffraction grating generates diffracted lights that travel in different directions depending on the wavelength as well as light that travels in a direction of reflection (regular reflection) that satisfies Snell's law when the surface of the diffraction grating is assumed as a mirror and light is called as zeroth-order light.

EXAMPLE

[0025] Here is described the quantitative design of a diffraction grating by reference to FIGS. 1, 2 and 3. First, assume that σ, or the grating constant of the diffraction grating (groove interval at the center of the diffraction grating) which is a basic parameter of the grating is 1/1200 mm whereas the wavelength to be optimized is 0.3 nm. Also assume that a set consisting of a light element (or a light compound) layers and a heavy element (or a heavy compound) layers are stacked in multiple layers to form a soft X-ray multilayer which has a periodic length D of 6.6 nm. The soft X-ray multilayer film is composed of two materials A and B and as shown in FIG. 1, the sum of the film thicknesses for these materials A and B is the periodic length D.

[0026] In order to maximize the diffraction efficiency, 1) the diffraction condition for the multilayer film coated diffraction grating, which is expressed by

[0027]

[Formula 6]

$$m_G\lambda = \sigma(\sin\alpha + \sin\beta) \qquad (1)$$

[0028] and

2) the Bragg condition for the multilayer coated diffraction grating, which is expressed by

[0029]

[Formula 7]

$$m_C\lambda = D(R_\alpha\cos\alpha + R_\beta\cos\beta) \qquad (2)$$

[0030] must be satisfied. Equation (2) is sometimes referred to as an extended Bragg condition. Here, λ is the wavelength of incident light, α is the angle of incidence measured from surface normal, and β is the angle of diffraction of the diffracted light also measured from the same normal line, with each angle being positive in the counterclockwise direction (see FIG. 1). In addition, R_α and R_β are respectively expressed by

[0031]

[Formula 8]

$$R_\alpha = \sqrt{1-(2\delta-\delta^2)/\cos^2\alpha}, \qquad (3a)$$

$$R_\beta = \sqrt{1-(2\delta-\delta^2)/\cos^2\beta}, \qquad (3b)$$

[0032] and if n is written for the average refractive index of the multilayer film (the weighted average based on the film thickness of the real part of the complex refractive indices of the two materials used in the multilayer film), δ = 1-7. Further, m_G is the diffraction order of the diffraction grating and m_C is the interference order of the multilayer film; in the Example under consideration, it is assumed that $m_G = m_C = 1$. FIG. 2 lists the values of the incidence angle α and the diffraction angle β at various wavelengths of the incident light that satisfy both equations (1) and (2) for the case where the materials pair in the multilayer film consists of Co and SiO_2 and where the respective layers have thicknesses of 2.64 nm and 3.96 nm. The materials pair of Co and SiO_2 was selected because it has no absorption edge in the wavelength region of 0.1-1 nm, thereby yielding high reflectance. Similar materials pairs are the set of cobalt and silicon carbide and that of cobalt and carbon.

[0033] Further, the optimum groove depth h, as obtained from equation (2.63) in Nonpatent Document 2, is

[0034]

[Formula 9]

$$h = \lambda/4\cos\alpha \qquad (4)$$

[0035] and in the case of the Example, h = 4.12 nm.

[0036] In addition, defining h for the depth of grooves, g_1 for the width of a land, and g_2 for the width of a valley, the optimum duty ratio (D.R.) is

[0037]

[Formula 10]

$$D.R. = \frac{g_1}{\sigma} = \frac{g_2 - h(\tan\alpha - \tan\beta)}{\sigma}, \quad (5)$$

[0038] and in the case of the Example, D.R. = 0.2878-0.3. The laminar-type diffraction grating fabricated under these conditions was furnished with the above-described multilayer film in 30 periods (i.e., periodic length D shown in FIG. 1 is stacked in 30 bilayers), thereby preparing a multilayer film coated diffraction grating; the diffraction efficiency of this grating was numerically calculated at various wavelengths and the results are shown in FIGS. 2 and 3.

[0039] FIG. 2 is a table showing the principal parameters of the laminar-type multilayer film coated plane diffraction grating according to the Example of the present invention; the table shows, for each wavelength, the directions in which incident light should be applied and diffracted light picked up in order to attain a maximum diffraction efficiency with the multilayer film coated diffraction grating described in the Example. FIG. 3 is a diagram showing the diffraction efficiency curve of the laminar-type multilayer film coated plane diffraction grating according to the Example of the present invention; it shows the diffraction efficiency of the multilayer diffraction grating of the Example that was used under the conditions shown in FIG. 2.

[0040] Thus, the diffraction grating according to the present invention is characterized in that it has a diffraction efficiency ten to a hundred times as high as that of the additional diffraction grating having a monolayer metal film added thereto. To summarize the reasons: first, the shape of grooves on the laminar-type diffraction grating is optimized by considering the specification of the multilayer; second, the present inventors discovered materials pairs for use in the multilayer film that would present high reflectance in the 0.1 - 1 nm region. The second observation is applicable to non-laminar-type diffraction gratings for use in the same wavelength region, including a blazed-type diffraction gratings having grooves of a saw-toothed shape and even reflectors.

Claims

1. A laminar-type multilayer diffraction grating having a multilayer film added to the surface, which multilayer being designed such that the angular conditions of incident light and diffracted light with respect to the use wavelength satisfy simultaneously (1) the formula of a diffraction grating and (2) an extended Bragg condition of a multilayer film coated diffraction grating, and further in addition, satisfy simultaneously (3) the groove depth that suppresses the zeroth-order light and (4) the condition for the ratio between the width of a land and the grating constant, further **characterized in that** the multilayer consists of a pair of two materials in multiple layers, each materials pair consisting of cobalt and silicon dioxide, cobalt and silicon carbide, or cobalt and carbon.

2. A blazed-type multilayer diffraction grating with grooves of a saw-toothed shape which has added to the surface a multilayer film made of at least one of the materials pairs according to claim 1.

3. The laminar-type or blazed-type multilayer film coated diffraction grating according to claim 1 or 2, wherein the interval between grooves on the grating is constant or varied.

Fig.1

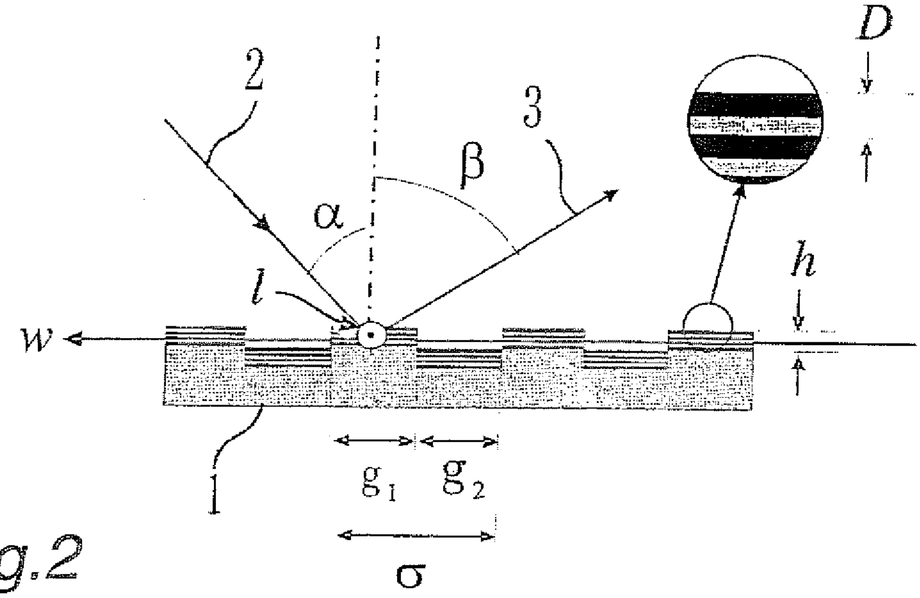
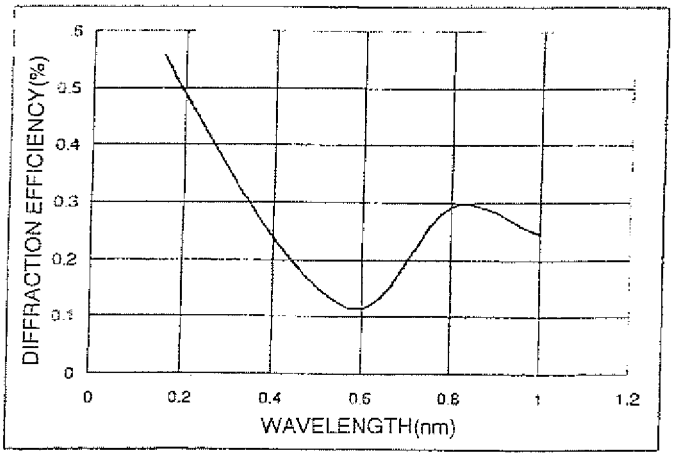


Fig.2

WAVELENGTH(nm)	n	α (DEGREES)	(DEGREES)
0.154	0.999986	89.63024	88.83807
0.2	0.999976	89.42676	88.61998
0.3	0.999944	88.95818	88.14277
0.4	0.999901	88.48438	87.66564
0.6	0.999779	87.91763	86.28583
0.8	0.999615	86.58563	85.76141
1	0.999418	85.64389	84.81699

Fig.3



INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2007/058291

A. CLASSIFICATION OF SUBJECT MATTER
G02B5/18(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G02B5/18

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Jitsuyo Shinan Koho	1922-1996	Jitsuyo Shinan Toroku Koho	1996-2007
Kokai Jitsuyo Shinan Koho	1971-2007	Toroku Jitsuyo Shinan Koho	1994-2007

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	Masato Koike et al., "Design of a high-efficiency grazing incidence monochromator with multilayer-coated laminar gratings for the 1-6 keV region", Review of Science Instruments, February 2006, Vol.77, p023101-1-4	1-3
Y	Edited by The Chemical Society of Japan, "5th edition Jikken Kagaku Koza 10 Busshitsu no Kozo II Bunko Ge", Maruzen Co., Ltd., 05 August, 2005 (05.08.05), pages 106 to 141	1-3
P,Y	JP 2006-133280 A (Japan Atomic Energy Agency), 25 May, 2006 (25.05.06), Full text; all drawings (Family: none)	1-3

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
28 June, 2007 (28.06.07)	10 July, 2007 (10.07.07)
Name and mailing address of the ISA/ Japanese Patent Office	Authorized officer
Facsimile No.	Telephone No.

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REFERENCES CITED IN THE DESCRIPTION

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Non-patent literature cited in the description

- **W. K. WARBURTON.** *Nucl. Instr. Meth. A,* 1990, vol. 291, 278 **[0004]**
- **M. KOIKE ; K. SANO.** The Fifth Series of Experimental Chemistry, Vol. 10, Spectroscopy and Diffraction II. Maruzen, 2005, vol. 10, 106-141 **[0004]**